AN ANALYSIS OF DC DISTRIBUTION SYSTEMS

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AN ANALYSIS OF DC DISTRIBUTION SYSTEMS

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To my parents

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LIST OF SYMBOLS AND ABBREVIATIONS

ΔV	Voltage Drop
φ	Power Factor Angle
E	RMS Voltage
f	Frequency
L	Inductance
P	Power Consumed
R	Cable Resistance
X	Cable Reactance
X_L	Inductive Reactance
AA	All Aluminum
AC	Alternating Current
ACSR	Aluminum Conductor, Steel Reinforced
CFL	Compact Fluorescent Light
DC	Direct Current
DOE	Department of Energy
DSS	Distribution System Simulator
EPRI	Electric Power Research Institute
GMR	Geometric Mean Radius
HVAC	Heating, Ventilating and Air Conditioning
HVDC	High Voltage Direct Current
ICCB	Insulated Case Circuit Breaker
IEEE	Institute of Electrical and Electronics Engineers
kV	kilovolt

kVA	kilo Volt Ampere
kVAr	kilo Volt Ampere-reactive
kW	kilo Watts
LED	Light Emitting Diode
MCCB	Molded Case Circuit Breaker
MVA	Mega Volt Ampere
MVAr	Mega Volt Ampere-reactive
PHEV	Plug-In Hybrid Electric Vehicles
PC	Personal Computer
PV	Photovoltaic
RMS	Root Mean Square
UPS	Uninterruptible Power Supply
V	Volts
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
W	Watts
WinIGS	Integrated Grounding Systems Analysis Program for Windows

SUMMARY

The Master's Thesis research focuses on analyzing the possibilities of using Direct Current distribution systems to distribute power to end users. Considering the shift in load types in the past few decades and also a growing demand of distributed generation, DC distribution can potentially offer higher efficiencies and cost savings to utilities. The incorporation of DC distribution offers the opportunity to eliminate multiple conversion stages for devices which are powered using DC electricity. The integration of power sources such as photovoltaics and fuel cells, which produce DC power, offer further incentives to consider the use of DC systems. Further, the projected growth is the use of plug-in hybrid electric vehicles means that charging facilities would need to be incorporated into the distribution system and using DC systems can help eliminate the conversion losses associated with rectifiers and inverters which would be part of the infrastructure if AC distribution was used. In the literature, the study of DC distribution has been limited to customized systems. The objective of this research is to analyze DC distribution when applied to systems based on standard IEEE test feeder systems. The IEEE 13 node test feeder and the IEEE 37 node test feeder will be used as the basis for the analysis. Issues such as associated costs, protection and integration of appliances will also be addressed.

CHAPTER 1

INTRODUCTION

The end of the nineteenth century witnessed a revolution in the electric power industry. A struggle between the DC system proposed by Thomas Edison and the AC system developed by George Westinghouse and Nikola Tesla ended with the triumph of AC. This was mainly due to the invention of the electrical transformer which allowed voltage to be stepped up to high levels, thus allowing transmission of power over long distances. Another contributor was public policy which demanded that power plants be located away from densely populated regions. The types of loads and generation at that time found AC favorable but with the advent of distributed generation and an increase in electronic loads, DC distribution systems may offer higher efficiency.

A looming deficit in the supply and demand of electricity and growing environmental concerns have made possible the development of alternative energy sources like photovoltaic systems and fuel cells. These sources produce DC power. Currently this DC power output is converted to AC using inverters and is fed to the home (or back to the grid). This conversion process leads to lesser efficiency due to the multiple converter losses involved.

This is brought into sharper perspective when we consider the types of loads we now have in the home. Computers, cell phone chargers, modern lighting systems and other ubiquitous electronic devices all function on DC power. These devices all have converters which convert the AC voltage of the supply to DC and this conversion also causes losses. Electronic loads also produce harmonics in AC systems which adversely affect power quality.

For critical facilities that make use of an uninterruptible power supply which utilizes the storage power of commercially available batteries, the incoming AC supply is first converted DC which is used to charge the standby battery and is converted back to AC. Now this AC supply serves several electronic loads where it is reconverted to DC and every additional conversion stage leads to losses. If DC supplies were incorporated into this system, several conversion stages would be eliminated which would increase the efficiency and lead to more easy integration of distributed energy resources and also help in the case of formation of micro-grids during periods of islanding.

The rising demand for plug-in hybrid electric vehicles (PHEVs) is expected to rise in the next few years. Utilities would have to construct extensive charging infrastructure which can be at home level, integrated into parking lots or new power parks. Power sources will be stretched to the limit and improving efficiency can lead to huge cost savings for utilities. Again, the elimination of conversion stages in powering PHEVs can represent large savings for utilities.

DC systems hold the potential for improving the efficiency of power distribution systems. However there needs to be an in-depth analysis of the theorized advantages imparted by DC distribution. Standards need to be in place to determine the most efficient path to migrating to DC systems, if indeed these systems really offer any advantages. An important aspect that needs to be examined is the cost analysis of these systems and migration issues.

1.1 Research Objectives

The following tasks have been carried out to analyze DC distribution systems:

- Literature study of DC distribution and their analysis on customized systems
- Simulation of systems based on the IEEE 13 node and 37 node test feeders
- Simulation and analysis of these systems under DC power
- Review of appliance integration and system protection issues
- Review of DC distribution economics

CHAPTER 2

OPPORTUNITIES FOR DC DISTRIBUTION

The nature of the electric system during the start of the 20th century, government policies that required power generating facilities to be located at central locations and the technological innovations in AC systems meant that the DC power system proposed by Thomas Edison lost out to the AC system proposed by Nikola Tesla and George Westinghouse. The electrical system today is very different from the system of those early days. There are several reasons to believe DC distribution offers a better alternative for the electrical system today.

2.1 Changes in Load Types

The common loads present in the electrical system for the majority of its existence were such that it made more technical and economical sense to operate them using AC. But the silicon revolution has had a profound effect on the most common loads present in the system. Computers are now ubiquitous and several of the loads in an average home or office are electronic in nature. These loads all operate on DC and are still supplied by the legacy AC distribution system. The figure below shows the distribution of electricity by end use in US households as reported by the Department of Energy in 2001.

Not only is power wasted at every stage where AC power is converted to DC and fed to these loads but the switching of these converters gives rise to harmonics in the ac supply which have a detrimental effect on the quality of power. A total harmonic voltage distortion of 5% and below is recommended for systems below 69kV [1]. DC systems would help in the reduction of this harmonic distortion.

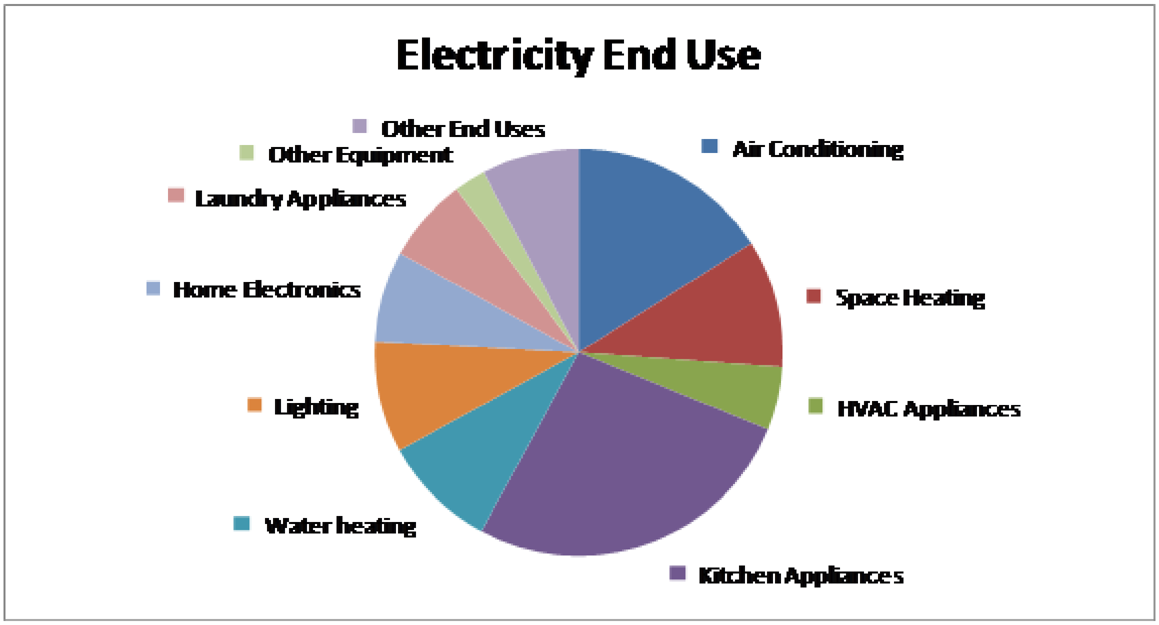


Figure 2.1: Electricity end-use proportion statistics (DOE, 2001)

2.1.1 A Case for Data Centers

During the early 1990s, with the advent of client-server computing, Data centers started gaining prominence. Data centers in the USA used 61 billion kWh of electricity in 2006 and this demand is projected to grow by 12% every year [2]. This represented 1.5% of all the electricity consumed in the US. Almost 11% of this energy is lost during the conversion processes and battery charging [3].

The nature of data centers calls for a very reliable power supply infrastructure. For the servers, it is critical that they be supplied by a reliable source with no variation in power quality. This means that data centers employ large numbers of Uninterruptible Power Supplies (UPS). In a UPS there is a conversion step from AC to DC in the first stage. The DC line is paralleled with a battery block which is charged by the AC grid under normal conditions. This DC is converted back to AC and fed to the servers where again a conversion from AC to DC takes place. The following figure shows the typical electrical system for a data center.

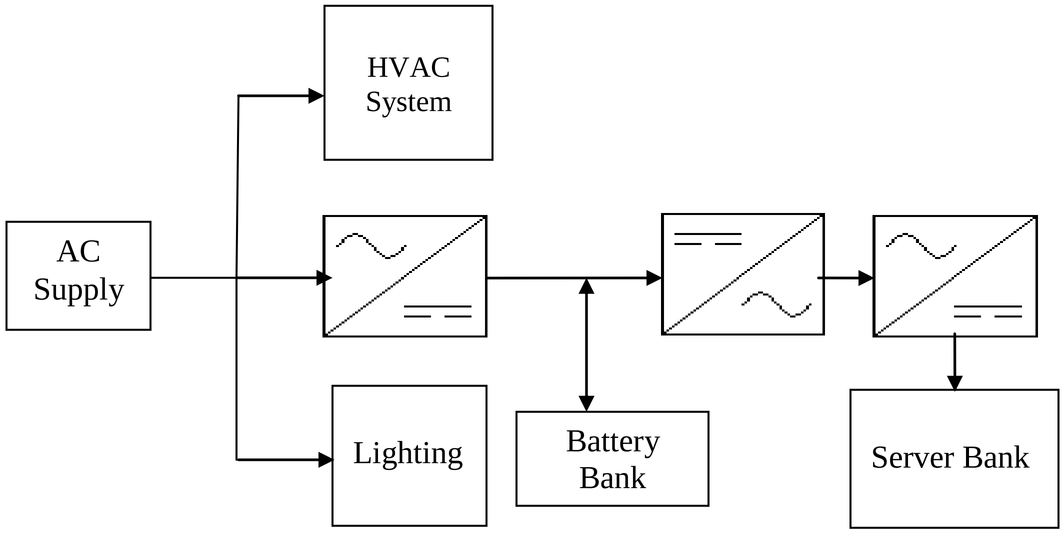


Figure 2.2: Typical layout of a data center power suppply system

These multiple conversion stages lead to losses in the system which can be avoided if DC distribution can be adopted. Commercially available lead acid batteries, which are generally used in a UPS, can be charged directly using the DC system with minimal conversion losses. If the grid supply is cut off, the power supply function can be seamlessly transferred to the battery bank.

2.1.2 HVAC systems

Another important load type today is the Heating, Ventilating and Air Conditioning (HVAC) systems. The energy consumed by HVAC systems accounts for nearly 31% of electricity end use in the residential sector and 30% in the commercial sector [4]. Also, cooling accounts for 50% of the electricity use in data centers [3]. Variable speed drives (VSD) have become increasingly popular in HVAC systems. The way a VSD operates is in some ways similar to a UPS. The typical figure of a VSD is shown below.

The incoming AC power is converted to DC and this DC is then converted into a variable voltage variable frequency wave by the drive and used to feed the motor which drives the compressor of the HVAC system. The motors used are usually induction motors though brushless DC motors have higher efficiencies at fractional horsepower ratings [5]. Thus, the elimination of one converter stage from AC-DC for the VSD will lead to higher efficiency and also does not add significantly to retrofitting costs.

2.1.3 Lighting loads

Lighting accounts for 9% of home and 38% of commercial electricity consumption. In 2006, Compact Fluorescent Lights (CFLs) accounted for nearly 20% of the total lighting market share in the USA [6]. With incandescent lights set to be phased out by 2014, CFLs that function with electronic ballasts will be heavily used for lighting purposes. Due to these ballasts, CFLs can be used both with DC as well as AC power supplies and hence retrofitting would not pose problems.

Light Emitting Diodes (LEDs) are another high lifetime source of lighting that is gaining prominence. These sources use solid state electronics to generate light of high luminosity and have a life time in excess of 20 years. Currently, high costs are keeping them well out of reach for consumers but they have been adopted in many specialized applications.

2.2 Distributed Generation

The traditional radial power flow system which was the basis of the legacy electricity infrastructure is becoming outdated. With distributed generation sources gaining prominence, there are scenarios under which DC distribution could be more advantageous compared to AC distribution systems. Two of the most promising distributed generation technologies viz. photovoltaics and fuel cells would most benefit from DC distribution.

2.2.1 Photovoltaic Energy

Total shipments of Photovoltaic (PV) modules and cells increased more than 90% in 2008, to nearly 1 million peak kilowatts [7]. With the increasing costs of conventional energy, solar cells are well on the path to achieving grid parity. PV cells are DC sources and in order to be connected to the AC grid, the solar panel power is converted to AC in an inverter module which is a standard part of a PV system. The block diagram below outlines the typical photovoltaic system.

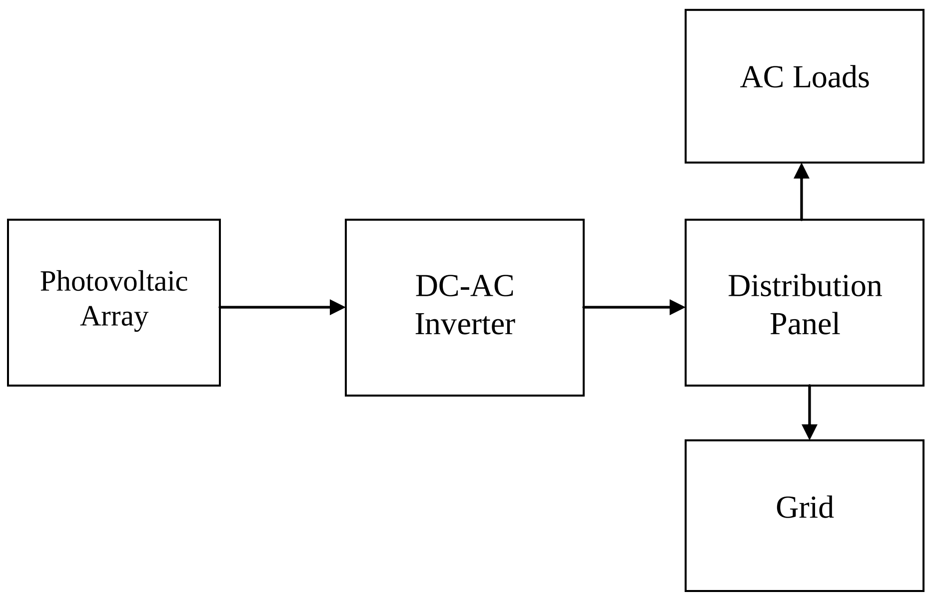


Figure 2.3: Layout of a photovoltaic system

This conversion causes unnecessary losses which could be avoided using DC systems. Thus DC distribution systems may well hold the key for PV panels to become a mainstream electricity resource.

2.2.2 Fuel Cells

Shipments of fuel cells rose 70% in 2007 [8] and with the US government's target cost of 30$/ kW by 2015 firmly in sight, fuel cells are becoming an important distributed generation resource. Fuel cells have been put into use by thousands of companies for primary and back-up power [9]. A fuel cell simply uses the chemical reaction between hydrogen and oxygen to produce DC voltage. Thus, we see again that conversion losses from DC to AC can be avoided by using a DC system in conjunction with fuel cell technology.

2.3 Plug-In Hybrid Electric Vehicles

With growing environmental concern about emissions from vehicles and rising fuel prices, much emphasis is being given to further research on Plug-In Hybrid Electric Vehicle (PHEV) technologies. It is forecasted that there will be 1.7 million PHEVs on the world's roadways by 2015 [10]. PHEVs can offer many advantages to the electricity grid itself. A standard road vehicle spends much of its time stationary. Electric vehicles, when interfaced with grids provide the opportunity of peak shaving and energy storage.

Batteries inside PHEVs are DC sources and the charging infrastructure involved, which converts AC power from the grid to DC, causes conversion losses. While the overnight slow home charging is one of the options for a PHEV, there is much motivation to integrate charging facilities inside common car parks to provide high power fast charging [11]. A combination of DC distribution and bi-directional DC-DC converters can pave the way for these smart car parks which can help utilities to make full use of the advantages offered by PHEVs.

CHAPTER 3

LOSS COMPARISON OF AC AND DC SYSTEMS

The most important factor in favor of DC distribution is that a large number of loads today function on DC power. Relying on AC distribution, with subsequent conversion to DC in order to serve these loads, leads to conversion losses. These losses can be eliminated if DC distribution is used. However the economic impact of investing in DC distribution by the utilities must be taken into account while considering savings made by avoiding conversion losses.

3.1 Reactive Power Losses

Distribution lines (as well as transmission lines) have an inductance and also a small value of capacitance. Many loads also exhibit inductive characteristics. This causes the sinusoidal AC current waveform in the circuit to lag behind the voltage wave by an angle φ, the cosine of which is called the power factor. More inductive the circuit, lower the power factor. A lower power factor implies that more current needs to be supplied by the source to power the same load than it would have in the absence of the inductive reactance. This excess current causes higher losses in the circuit as a resistive loss increases in proportion to the square of the current.

Further, the inductive reactance of the circuit is given by,

$X_L = 2\pi f L$

where,

$f =$ The system frequency i.e. 60 Hz.

$X_L =$ The inductive reactance

$L =$ The inductance of the circuit

The increase in cost to the utility due to the decrease in power factor is passed on to the consumer in the form of a low power factor penalty fee. Hence, in order to mitigate the effects of low power factor, in areas containing large inductive loads, for example factories, large capacitors banks are connected in parallel with the loads. This helps raise the power factor of the load.

In DC distribution systems, as the frequency is zero, the inductive reactance is zero. Power factor is always maintained at unity and this leads to higher savings the utility and hence the consumer. A substantial reduction in losses may be gained by using DC distribution.

3.2 Conversion Losses

Another major source of losses in AC systems supplying DC loads is the converter loss. Conversions from AC to DC, DC to AC and between two different DC voltage levels always give rise to losses. Also these losses vary according to the amount of rated load. For desktop PCs, at 20% to 25% of the load where many PCs commonly operate, the efficiencies range from 60.5% to 82.5%. For servers the power supply efficiency ranges from 67.7% to 81.3% at full load, from 68.6% to 83% at 50% load and from 58.5% to 78.4% at 20% load [12]. All these losses can be reduced by moving to DC distribution.

Of course, DC distribution cannot eliminate all the problems. When a step down from higher voltage level to a lower voltage occurs using a buck converter in a DC distribution system, the efficiency would vary with the percentage of load. However, a paralleling DC-DC converter topology [13], describes design improvements that allow DC-DC converters to operate close to the maximum operating efficiency until 10% of operation.

Also, with the advent of high power DC-DC converters, the conversion process is seamless and is possible for higher voltage levels [14]. It is essential that high power DC-DC converters be developed for DC distribution systems.

3.3 Loss Calculation

In [15], the authors have analyzed an existing facility using DC as a case study. In order to determine the appropriate voltage level to be used within residential or commercial facilities, we must examine the voltage drops and power losses associated with the various proposed voltage levels.

National electric standards specify that the voltage drop within the internal wiring be no more than $\pm$5% This and the current rating of existing cables will allow us to determine the optimum voltage levels that can be used with residential and commercial facilities. The voltage drop in the cables for single phase loads is calculated as:

$$\Delta V = 2\left(R\frac{P}{E} + X\frac{P}{E}tan\varphi\right)$$

where, $\Delta V = The\ voltage\ drop\ along\ the\ cable$

$P = The\ power\ consumption\ of\ the\ load$

$E = The\ rms\ (line\ to\ neutral) voltage$

$R = The\ cable\ resistance\ calculated\ at\ 80°C$

$X = The\ cable\ reactance$

$\varphi = The\ power\ factor\ angle\ of\ the\ load$

Similarly, we determine the voltage drop in the cables for three phase loads using the following equation:

$$\Delta V = \frac{1}{\sqrt{3}}\left(R\frac{P}{E} + \ X\frac{P}{E}tan\varphi\right)$$

The power loss in the cables for single phase and three phase circuits respectively is given by:

$$\Delta P = \ 2R\left(\frac{P}{Ecos\varphi}\right)^2$$

and,

$$\Delta P = \frac{R}{3}\left(\frac{P}{Ecos\varphi}\right)^2$$

CHAPTER 4

TEST SYSTEMS AND SIMULATION

It is important to test the hypothesis that DC distribution can offer high efficiencies. The methodology to be adopted is to simulate test systems on AC distribution and under DC distribution. The losses in the circuit each case can then be analyzed and can give a quantitative measure of loss reductions.

4.1 Test Systems

The testing will be carried out on two different systems. In the literature, the approach has been to use custom designed systems to test the efficiency of DC distribution. The approach in this research is to test DC distribution on systems based on standard distribution test systems. This can provide a more realistic view of the advantages offered by DC distribution and adoption by utilities.

In 1991, the IEEE PES Distribution System Analysis Subcommittee working group started out as an informal task force and developed four radial test feeders for testing distribution systems. There are several test feeder cases such as the 13-bus feeder, the 34-bus feeder, the 37-bus feeder, the 123-bus feeder, etc. The test feeders to be used as the basis for the systems in this project are the 13-bus or 13-node feeder and the 37-node test feeder.

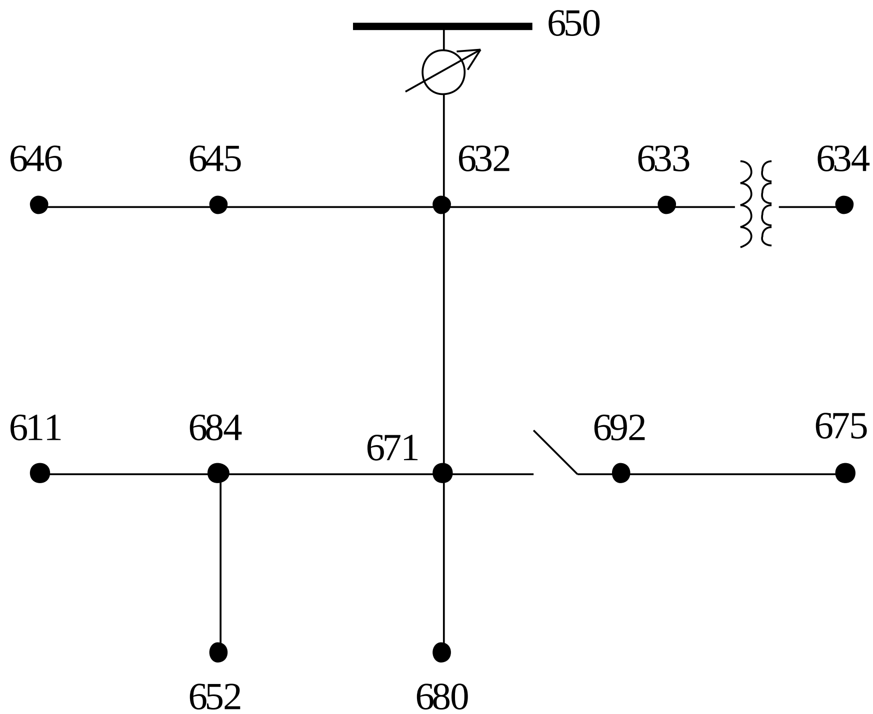


Figure 4.1: The IEEE 13-node test feeder

The figure above shows the layout of the 13-bus system. This system is a basic distribution system and contains several overhead distribution lines and also some underground cables. The details of the system are given in Appendix A.

The other system, on which the second test system is based, is the IEEE 37-bus system. This system is an example of an underground cable distribution system. The figure below shows the layout of this system. The details of this system are given in Appendix B.

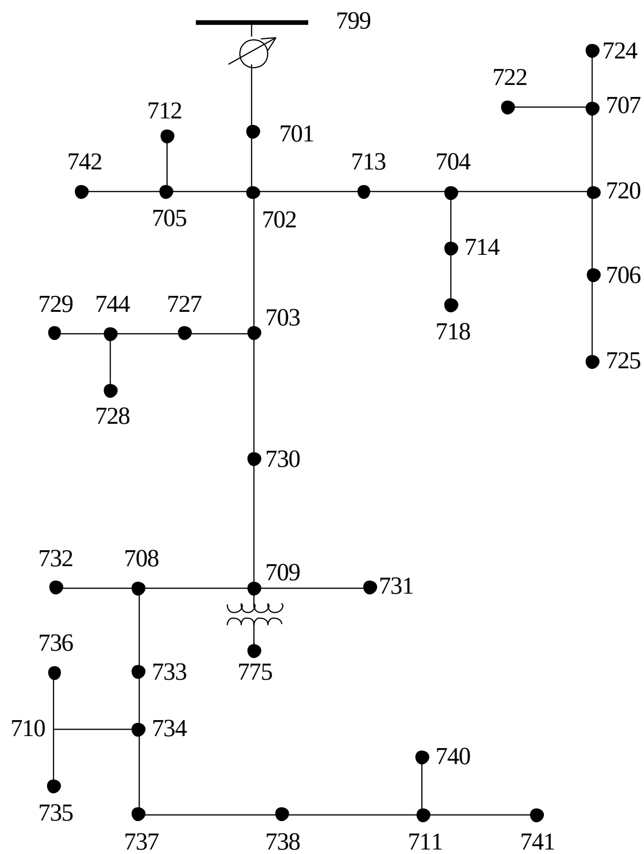


Figure 4.2: The IEEE 37-node test feeder

4.2 Simulation Software

The software packages considered to carry out the simulations were Open DSS and WinIGS-T. There are not many software packages which can effectively simulate distribution systems and the two software packages mentioned are best suited for the task. The following sections describe the software and reasons for selecting WinIGS-T.

4.2.1 Open DSS

Open Distribution System Simulator or Open DSS is an electrical system simulation tool for utility distribution systems. This is an open source software package developed by the Electric Power Research Institute (EPRI). The Open DSS can be implemented both as a standalone EXE program and also as a COM DLL [16]. The figure below shows the DSS standalone application.

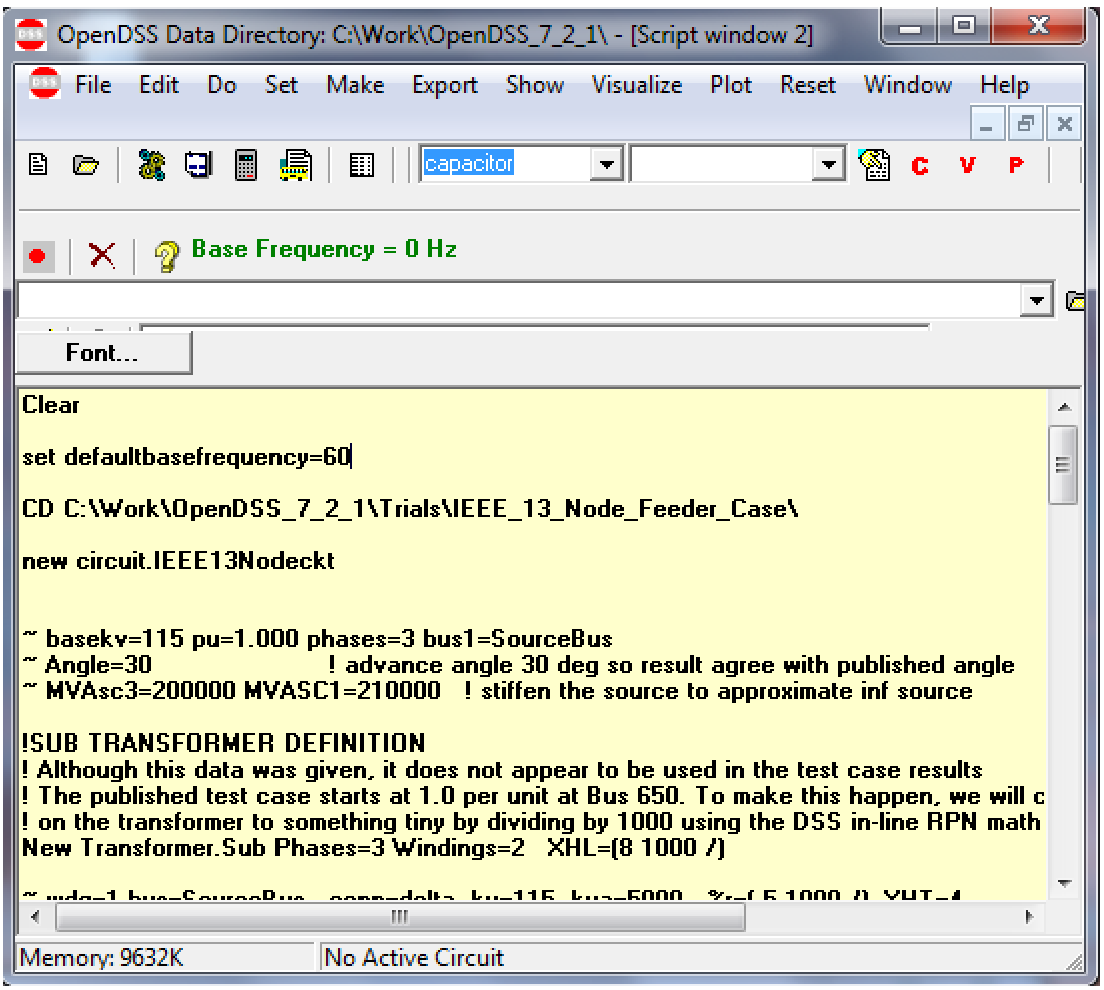
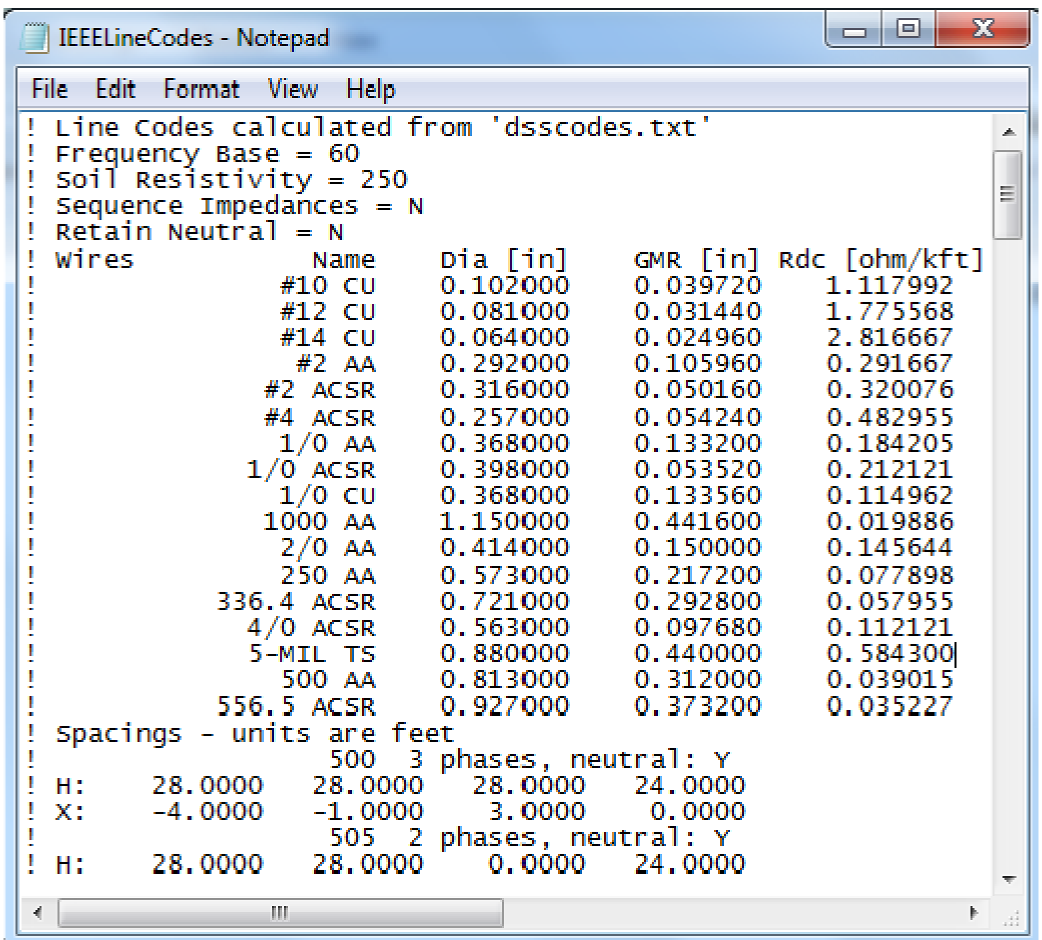


Figure 4.3: Open DSS EXE application

Open DSS allows for wide flexibility in defining various aspects of the distribution system. The DSS supports all RMS frequency domain analyses performed on electric power distribution systems. Power flow, harmonic analysis and fault current calculations can be carried out on DSS and it also has options to integrate daily load variation, etc. For overhead lines and underground cables, the configurations can be defined as also the types of conductors used. Transformer models are also available and also regulators along with loads. The figure below shows line definitions in Open DSS.


IEEELineCodes - Notepad

File Edit Format View Help

```
! Line Codes calculated from 'dsscodes.txt'
! Frequency Base = 60
! Soil Resistivity = 250
! Sequence Impedances = N
! Retain Neutral = N
! Wires                Name     Dia [in]     GMR [in]  Rdc [ohm/kft]
!                   #10 CU    0.102000     0.039720     1.117992
!                   #12 CU    0.081000     0.031440     1.775568
!                   #14 CU    0.064000     0.024960     2.816667
!                    #2 AA    0.292000     0.105960     0.291667
!                  #2 ACSR    0.316000     0.050160     0.320076
!                  #4 ACSR    0.257000     0.054240     0.482955
!                   1/0 AA    0.368000     0.133200     0.184205
!                 1/0 ACSR    0.398000     0.053520     0.212121
!                   1/0 CU    0.368000     0.133560     0.114962
!                  1000 AA    1.150000     0.441600     0.019886
!                   2/0 AA    0.414000     0.150000     0.145644
!                   250 AA    0.573000     0.217200     0.077898
!               336.4 ACSR    0.721000     0.292800     0.057955
!                 4/0 ACSR    0.563000     0.097680     0.112121
!                 5-MIL TS    0.880000     0.440000     0.584300
!                   500 AA    0.813000     0.312000     0.039015
!               556.5 ACSR    0.927000     0.373200     0.035227
! Spacings - units are feet
!                    500   3 phases, neutral: Y
! H:      28.0000    28.0000    28.0000    24.0000
! X:      -4.0000    -1.0000     3.0000     0.0000
!                    505   2 phases, neutral: Y
! H:      28.0000    28.0000     0.0000    24.0000
```

Figure 4.4: Line definitions in Open DSS

Defining loads in Open DSS is also accomplished by means of a text based file which is imported into the Open DSS program. The image below shows the scripts required to define new loads in DSS.

```
IEEE123Loads - Notepad
File  Edit  Format  View  Help

! LOAD DEFINITIONS

New Load.S1a   Bus1=1.1    Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S2b   Bus1=2.2    Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S4c   Bus1=4.3    Phases=1 Conn=Wye   Model=0 kV=2.4   kW=40.0 kvar=20.0
New Load.S5c   Bus1=5.3    Phases=1 Conn=Wye   Model=3 kV=2.4   kW=20.0 kvar=10.0
New Load.S6c   Bus1=6.3    Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S7a   Bus1=7.1    Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S9a   Bus1=9.1    Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S10a  Bus1=10.1   Phases=1 Conn=Wye   Model=3 kV=2.4   kW=20.0 kvar=10.0
New Load.S11a  Bus1=11.1   Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S12b  Bus1=12.2   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S16c  Bus1=16.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S17c  Bus1=17.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S19a  Bus1=19.1   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S20a  Bus1=20.1   Phases=1 Conn=Wye   Model=3 kV=2.4   kW=40.0 kvar=20.0
New Load.S22b  Bus1=22.2   Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S24c  Bus1=24.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S28a  Bus1=28.1   Phases=1 Conn=Wye   Model=3 kV=2.4   kW=40.0 kvar=20.0
New Load.S29a  Bus1=29.1   Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S30c  Bus1=30.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=40.0 kvar=20.0
New Load.S31c  Bus1=31.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S32c  Bus1=32.3   Phases=1 Conn=Wye   Model=1 kV=2.4   kW=20.0 kvar=10.0
New Load.S33a  Bus1=33.1   Phases=1 Conn=Wye   Model=3 kV=2.4   kW=40.0 kvar=20.0
New Load.S34c  Bus1=34.3   Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S35a  Bus1=35.1.2 Phases=1 Conn=Delta Model=1 kV=4.160 kW=40.0 kvar=20.0
New Load.S37a  Bus1=37.1   Phases=1 Conn=Wye   Model=2 kV=2.4   kW=40.0 kvar=20.0
New Load.S38b  Bus1=38.2   Phases=1 Conn=Wye   Model=3 kV=2.4   kW=20.0 kvar=10.0
```

Figure 4.5: Load definition in Open DSS

4.2.1.1 Advantages of Open DSS

- Open source software with modifiable source code
- Can be controlled from MATLAB or Visual Basic
- Simple syntax to define line geometry, line parameters, load parameters, etc.
- Geared towards distribution systems

4.2.1.2 Disadvantages of Open DSS

- Lack of a visual interface makes it unintuitive
- Lack of the AC-DC converter or other power electronics models

4.2.2 WinIGS-T

Integrated Grounding Systems Analysis program for Windows or WinIGS-T carries out time domain analysis of grounding systems. Though WinIGS is not particularly geared towards carrying out analysis of distribution systems, it has enough flexibility and a large database of cables, overhead lines and other typical distribution system components and can easily be adapted to analyze the two test systems.

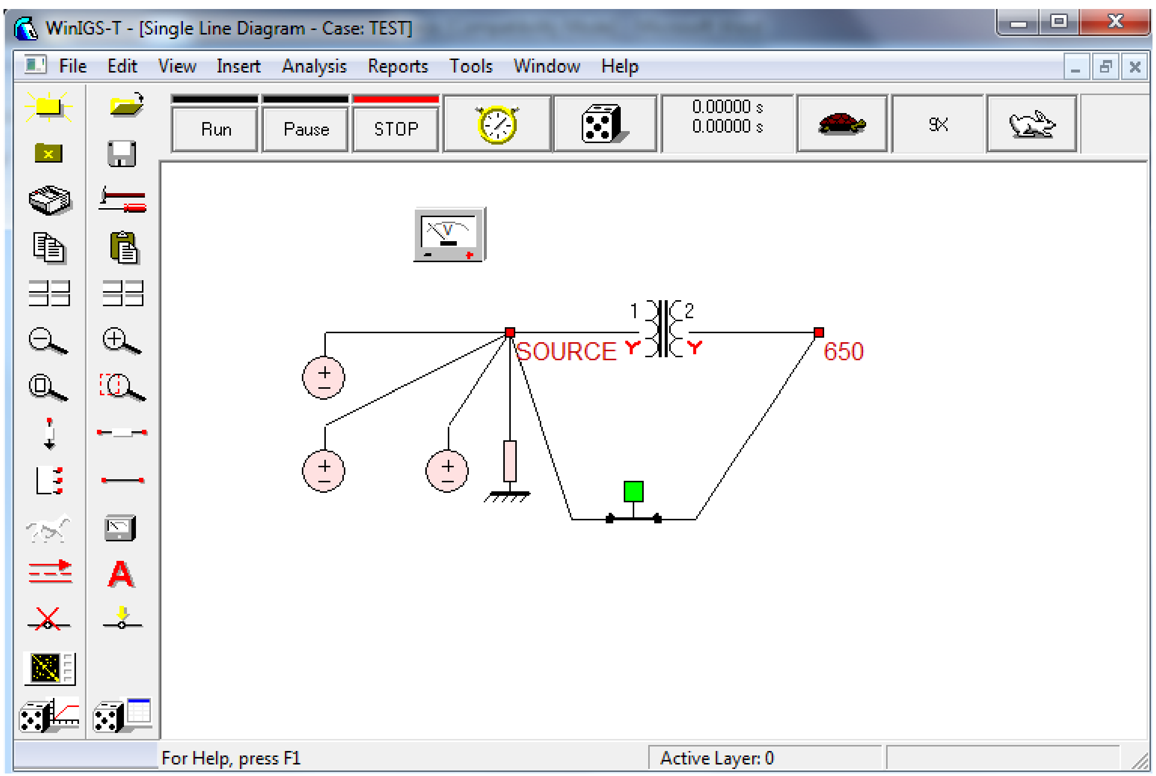


Figure 4.6: WinIGS user interface

The above figure shows the visual interface of WinIGS. It is very intuitive and the various device models can be dragged and dropped to create a system. Win IGS contains a vast library of overhead transmission lines and cables. The figure below shows the conductor library for overhead lines provided in WinIGS.

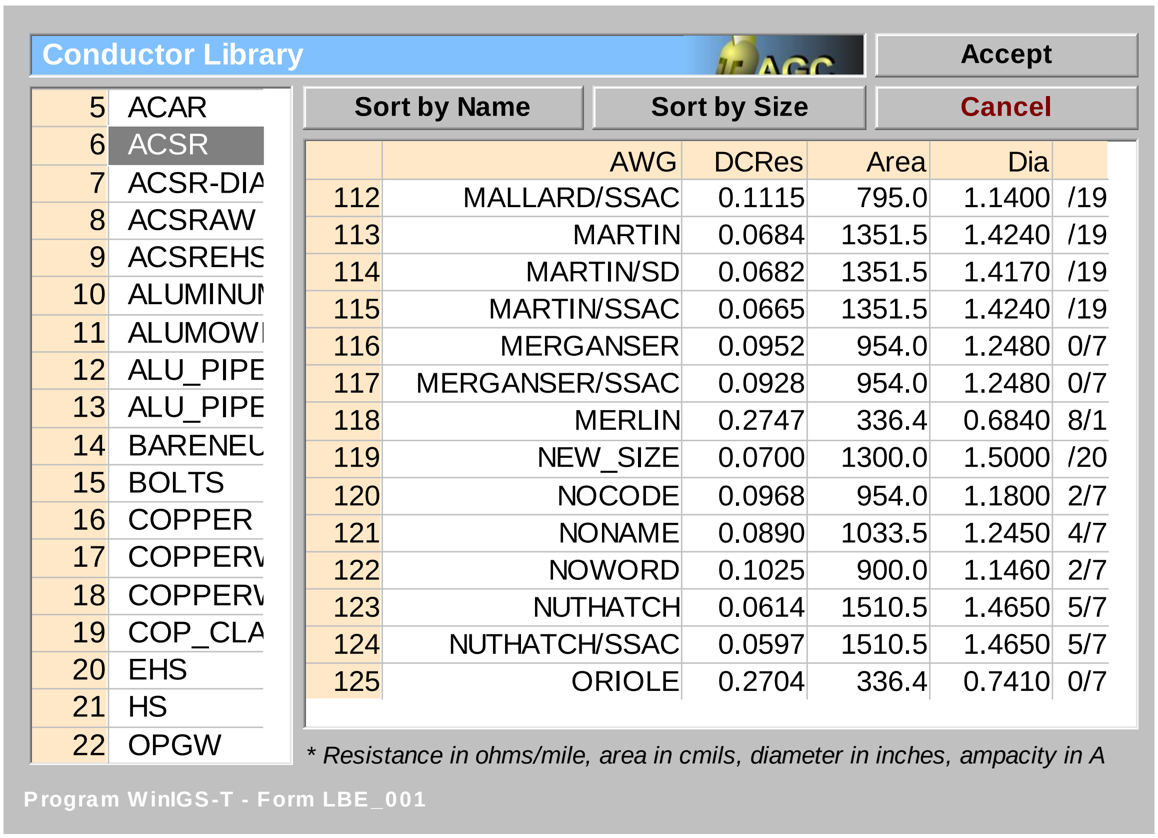


Figure 4.7: Conductor library in WinIGS

The configuration of distribution lines and underground cables is also done via a visual interface. This helps us to modify the GMR of lines so as to suit the test system's requirements. The two figures below show the arrangement of overhead lines and underground cables respectively.

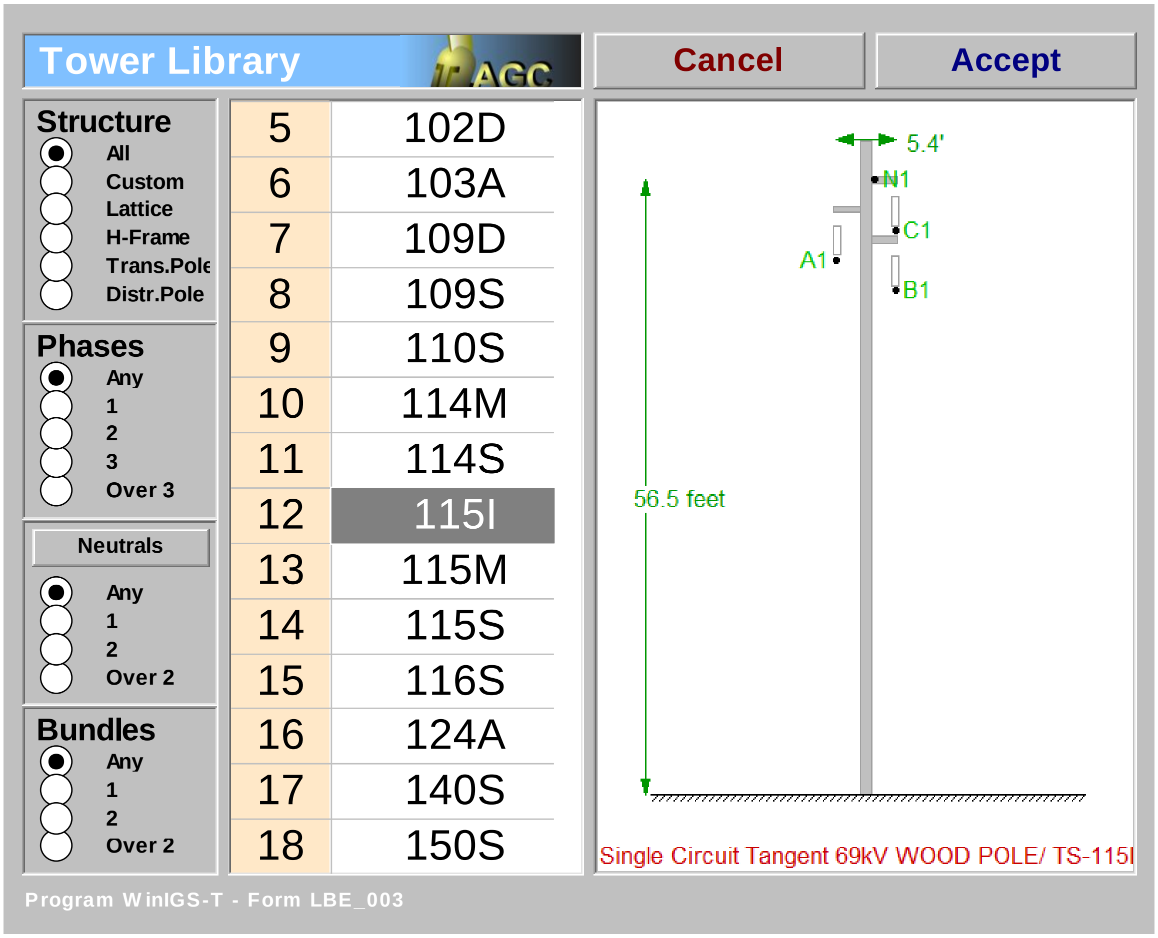


Figure 4.8: Overhead line configuration library in WinIGS

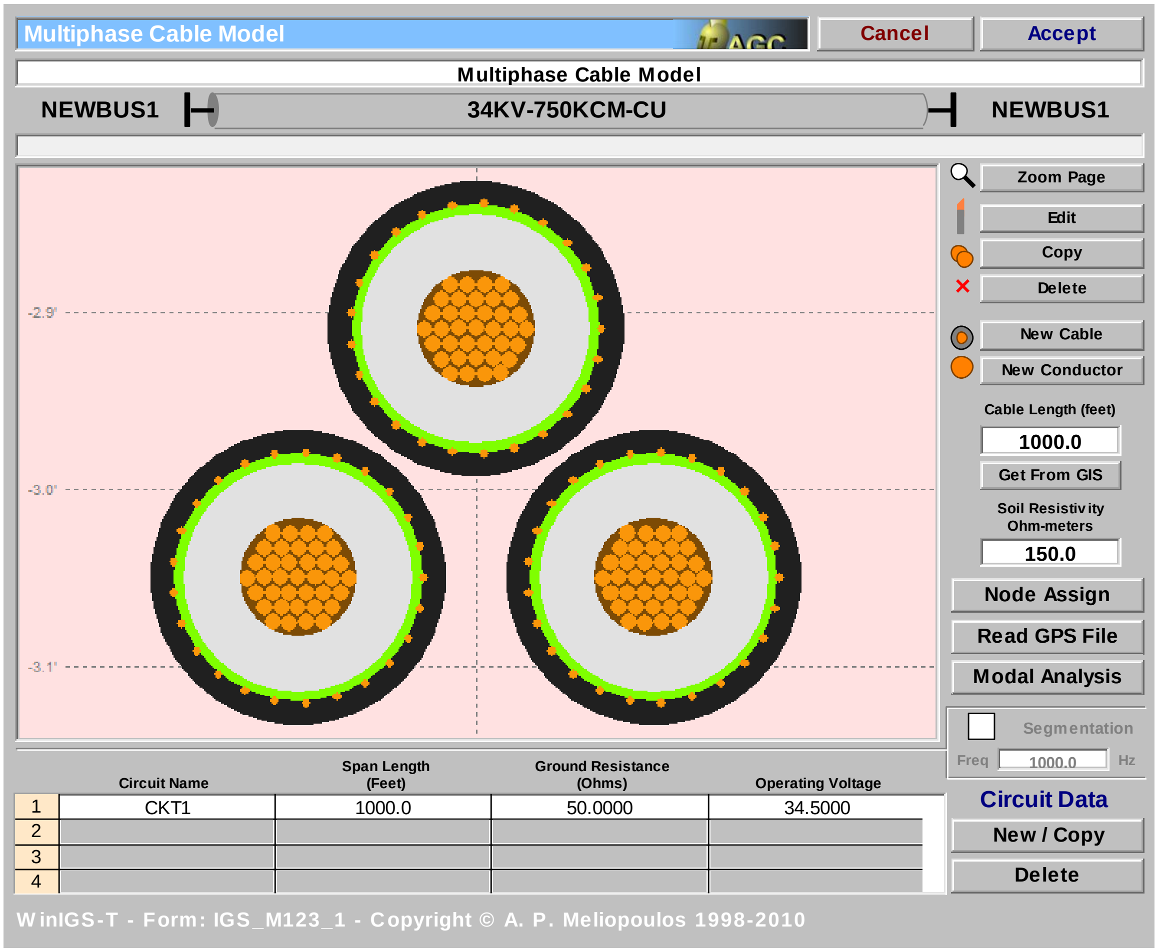


Figure 4.9: Multi-phase cable model in WinIGS

These databases in the software make it very easy to use and the test system can be simulated with minimum modifications. Another important component amongst the various device models in the WinIGS library is the transformer model. Transformers are an integral part of any distribution system and WinIGS has a detailed model for transformers which is shown in the figure below.

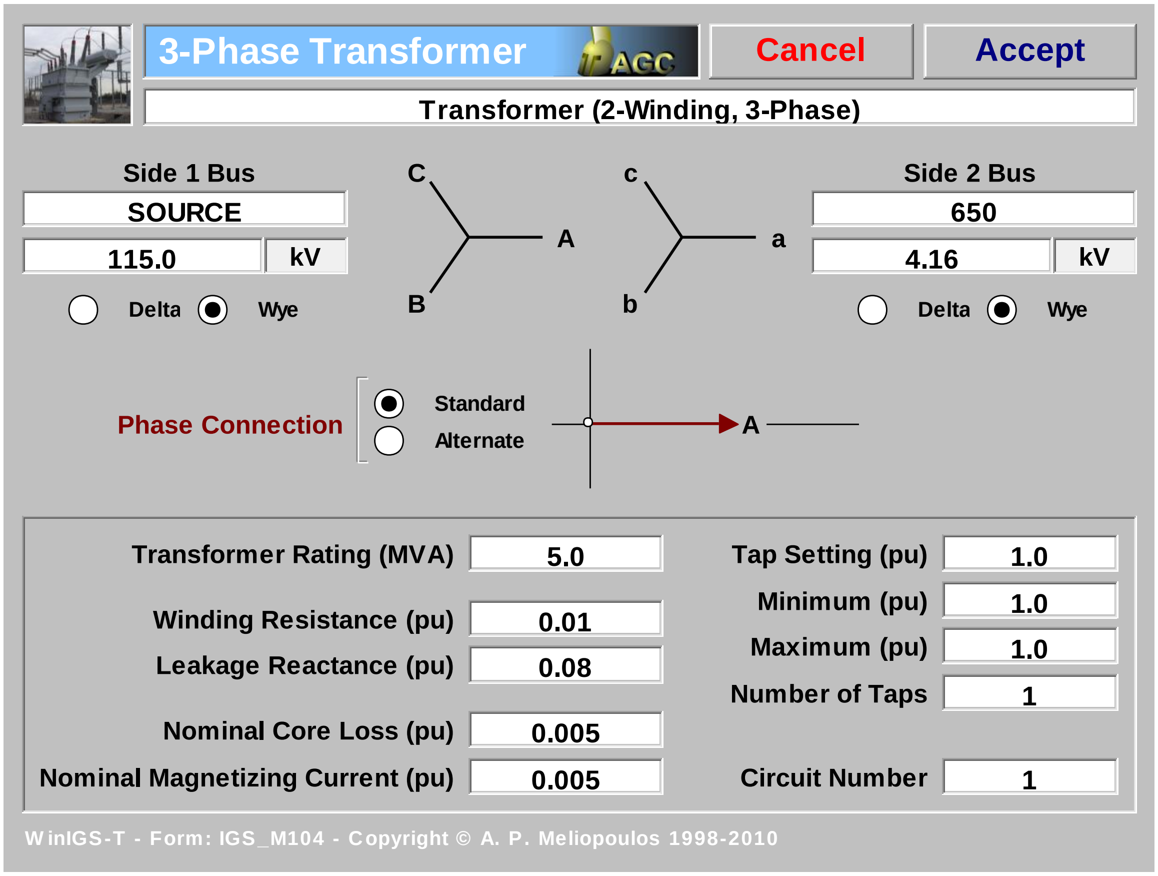


Figure 4.10: Transformer model in WinIGS

4.2.2.1 Advantages of WinIGS-T

- Visual interface which makes it very intuitive
- Large library of cables, overhead lines and other components
- AC-DC converter model which is important in this simulation
- Graphical displays of currents and voltages in the system

4.2.2.2 Disadvantages of WinIGS-T

- Geared primarily towards simulating grounding systems
- Difficult to implement unbalanced three phase loads

4.3 Simulation

Considering the advantages and disadvantages of both Open DSS and WinIGS-T, the latter would be best suited for the purposes of this research and is the software used to simulate the systems based on the IEEE 13-node test feeder and the IEEE 37-node test feeder.

The simulation results for the system based on the 13-node feeder are described in Appendix C. The results after simulating this system using an AC-DC converter are outlined in Appendix E. The simulation results for the system based on the 37-node feeder are described in Appendix D. The results after simulating the system based on the 37-node feeder using AC-DC converter are tabulated in Appendix E.

CHAPTER 5

INTEGRATION OF APPLIANCES

The transition from AC to DC distribution would be much easier to implement on new distribution systems. Modifying older distribution systems to reflect this change would be a difficult endeavor keeping in mind the fact that existing appliances are all meant to work on AC. However, in [17], the authors have demonstrated the possibility of using certain exiting appliances on DC power supplies.

The major advantages offered by DC distribution are for those appliances and devices that function on DC power such as computers and chargers for PHEVs. However there are certain appliances that can function without modification on AC as well as DC supply. This is true of purely resistive devices like heaters and ovens while some others might require modification.

5.1 Lighting Loads

One of the most important uses of electricity is to provide lighting and the integration of lighting loads in essential to making the transition to DC distribution systems. The most widely used lights for residential applications are incandescent lights, compact fluorescent lights and the emerging LED lights.

5.1.1 Incandescent Lights

These lights have been widely used in homes as well as commercial installations because of their low cost and ready availability. However they are very inefficient and are set to be phased out from the year 2014. The way these lights function is very simple. Electric current flowing through a tungsten filament inside a glass bulb causes the filament to glow due to heat and gives off electromagnetic radiation. This is a simple resistive load and can function equally well on AC as well as DC supply. There are some reports that DC supply decreases the life time of these lights but for practical purposes, they have an equal life under both AC and DC power supply.

5.1.2 Compact Fluorescent Lights

In the past few years, compact fluorescent lights (CFLs) have emerged as a major competitor to incandescent lights as well as normal fluorescent light tubes. Although they are more expensive than the tungsten bulbs, they have a longer lifetime and are much more efficient representing almost 40$ in savings over their life [18].

CFLs use a gas discharge tube and the electrons flowing from one electrode to the other excite the mercury atoms present in the tube. When the excited atoms return to the normal state they give off ultraviolet light which is converted into visible light by the phosphor coating on the inside of the discharge tube. All CFLs contain electronic ballasts. This ballast has rectifier circuits along with filter capacitors and this converts low frequency AC to high frequency AC because CFLs offer higher efficiencies at high frequencies. This makes CFLs particularly attractive for use in DC systems as they can be used without any modification. Efficiency might increase without the initial conversion to DC.

5.1.3 High Power LEDs

High power Light Emitting Diodes are the emerging lighting technology and the high investment costs are the only factor holding back these light sources from flooding the market. These lights have significantly longer life times and can last up to 20 years. The LEDs allow the flow of current in one direction and are in fact the basis of rectifier operation. These bulbs would function admirably on DC power supply. They are responsible for injecting harmonics into the AC supply and problem would be eliminated in DC supplies.

5.2 Variable Frequency Drive Systems

Many appliances and a majority of industrial loads employ the use of induction motors. Heating Ventilation and Air Conditioning (HVAC) systems accounting for almost 30% of electricity use in the residential and 30% in the commercial sector [4] and are run using induction motors. Appliances such as washing machines and refrigerators also need motors to function. Controlling the speed of the induction motors in several applications which are subjected to variable loads is the function of a Variable Frequency Drive (VFD) system.

VFDs are used to control the frequency of the input supply to the motors in order to increase motor efficiency under varying load. The basic block diagram of a VFD is shown in the figure below.

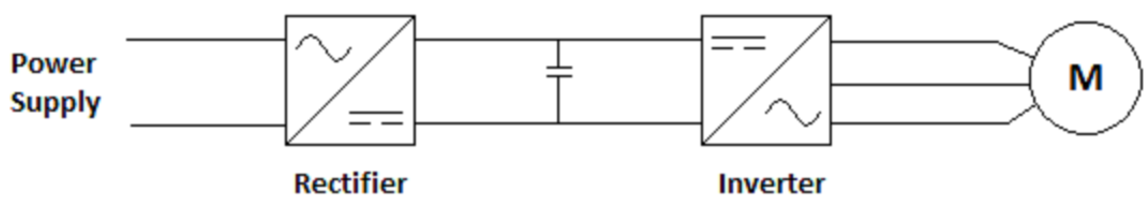


Figure 5.1: Block diagram of a variable frequency drive

As seen in the block diagram, the VFD first converts the incoming power supply into DC and reconverts it into an AC waveform of appropriate frequency which varies according to the load. This leads to higher efficiency and this system is widely used in HVAC systems worldwide. VFDs are also used in several industrial processes and can be modified to be used in ubiquitous home appliances such as refrigerators, which use a motor to drive the compressor and washers and dryers which usually use single phase motors to function.

For applications like these, which are deliberately grouped together because of similar advantages, DC distribution would help increase efficiency even more because of the elimination of the rectification stage. VFDs are responsible for injecting harmonics into the supply. Prior conversion to DC would help tackle the problem of harmonics by using centralized harmonic filters to help mitigate the problem.

5.3 Resistive Loads

Another common application of electricity is to drive the loads which are purely resistive in nature such as cooking stoves and ovens. These function equally well on AC as well as DC and there would be no significant changes required to these appliances under new DC distribution schemes. An appliance which functions on 220 Volts RMS would give the same performance under 220 Volts DC.

5.4 Electronic Loads

The important reason for which DC distribution must be given serious consideration is the increasing use of devices such as computers and mobile phone chargers which function on DC power supplies. In order to power these devices there is a process of rectification which can be eliminated and efficiency can be improved with the adoption of DC distribution.

5.5 Plug-In Hybrid Electric Vehicles

With environment friendly vehicles poised to penetrate the market within the next ten years, charging mechanisms for the plug-in hybrid electric vehicles (PHEVs) would play an important part in determining the use of DC distribution. Though not “appliances”, the integration of these vehicles is a topic that must be discussed as PHEVs are one of the prime motivators for the use of DC supply.

The obvious advantage for the use of DC distribution in the case of PHEVs is of course increased efficiency due to the elimination of the rectification stage which would cause some conversion loss. Mass parking/charging stations could offer smooth charging solutions for the PHEVs through a local DC distribution system. It has also been proposed that the energy stored in the batteries of PHEVs could be used by utilities in order to meet peak demand when these vehicles would usually not be in motion [19]. This requires efficient bi-directional flow of power, the efficiency of which can be hampered by conversion stages from AC to DC and vice-versa. DC distribution can offer opportunities for smooth bidirectional flow of electricity to meet the peak demand.

5.6 Distribution Lines and Cables

In [20], the authors discuss the feasibility of using the existing AC cables for DC distribution systems. The distribution lines can be three-wire or four-wire as shown in figures below.

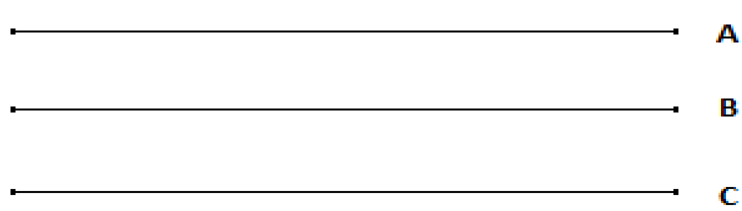


Figure 5.2: Three-wire AC system

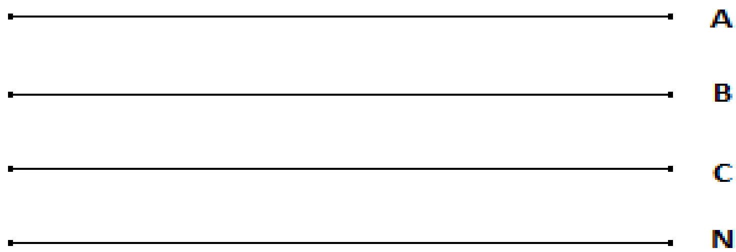


Figure 5.3: Four-wire AC system

One of the big advantages of using DC distribution is the savings in costs achieved by using fewer wires. The three wire system can be modified in two ways. If we have two separate voltage levels e.g. 230V DC and 115V DC, the three wire system can be modified as shown below.

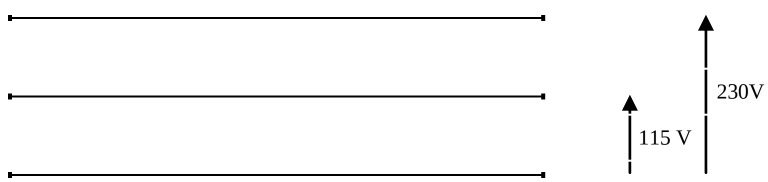


Figure 5.4: Three-wire DC with different voltage levels

Another option is using a single voltage level with one active phase wire, one neutral and one ground wire as shown below.

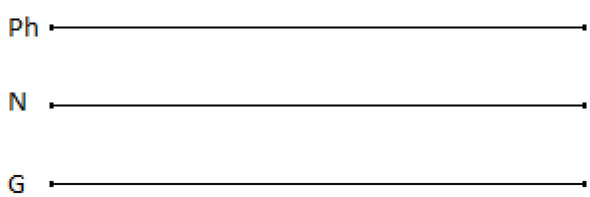


Figure 5.5: Three-wire DC with single voltage level

The challenge in powering appliances with DC lies in the selection of an appropriate voltage level. A single voltage level cannot be used to power high power devices such as ovens and devices which function at much lower voltages such as computers. Some form of DC-DC conversion would be required which leads to losses in high power applications. Appropriate network topologies which can accommodate various voltage levels could be one of the solutions to counter this disadvantage. Another would be the development of low cost, high efficiency DC-DC converters which can help overcome these issues.

CHAPTER 6

SYSTEM PROTECTION

There are some drawbacks to using DC distribution. Chief among them is the protection of DC systems. Many of the problems that can affect a DC distribution system are already well known in the mature HVDC technology.

6.1 AC-Side Protection

Protection is not only necessary on the DC side but also on the AC side. The AC side of the DC distribution system would have to be protected against any line and phase faults. This protection would typically take the form of pilot relaying. Circuit breakers which are triggered by relays monitoring both the voltage and current on the AC side of the AC-DC converter would commonly be used. This technology is already in place and has been used for several years. AC protection is not the biggest challenge for DC distribution.

The AC bus which would tie the AC system to the converter transformer would typically be protected using bus differential protection. The bus may also have harmonic filters (to damp out 11^{th} and 13^{th} harmonics) and reactive power support and both of these must have overvoltage protection. There would be a measurement on the converter bus and an overvoltage relay.

The converter transformer would have transformer differential relays and over-current protection would be provided as a back-up to the transformer differential protection. In larger transformers there would be sensors to monitor oil pressure and temperature, etc. and alarms to indicate problems. Since the power levels involved in DC systems are much lower than HVDC systems, protection systems will not be as expensive.

6.2 DC-Side Protection

The protection of the DC side can be a difficult proposition. In HVDC systems, for protection against large currents, the control valves are adjusted to lower the voltage at one end which in turn lowers the fault current. Thus the controls are an essential part of the DC protection. AC circuit breakers can open on the natural zero of a fault current and this reduces the possibility of an electric arc re-strike. However, this is not possible in DC circuit breakers due to the absence of a natural current zero. However there are ways to overcome these problems and they are discussed below.

6.2.1 Line Protection

There is a possibility of a line to ground fault occurring on the DC line. The voltage at the line terminal can be monitored by a DC voltage divider circuit. A ground fault will cause the voltage to drop to low levels at an extremely fast rate. The voltage which is monitored along with an apparatus to detect the rate of change of the voltage can be used to detect the ground fault on the DC line.

The rate of change of voltage can be monitored using simple differentiator circuits and on comparison with a suitable reference, can automatically cause the controls of the AC-DC converter to change the firing angle to reduce the DC side voltage, hence the current. Selectivity must be maintained to ensure that this protection scheme does not operate for the AC side faults.

6.2.2 Circuit Breakers

On the distribution side, for AC systems, protection functions are usually provided by simple circuit breakers like Molded Case or Insulated Case (MCCBs or ICCBs). In [21], the author discusses the use and change in the protection characteristics of the commonly used AC circuit breakers for DC applications.

For low voltage levels of 600V and below, these circuit breakers can be used for DC systems. Manufacturers will typically provide adjustments to the trip curves of the MCCBs. The effect of these adjustments is to slightly increase the stated AC magnetic tripping levels when the same circuit breaker is used in DC circuits.

One of the important differences between the interruption of AC and DC circuit breakers is the presence of the natural current zero in the AC current wave which lowers the degree of ionization and the arc does not reignite and the overcurrent is cleared. A DC current does not have a natural zero and hence the probabilities of arc re-strike increase. One of the ways to compensate for this is by the use of a resonant circuit which forces the DC current to zero before initiating the arc interruption [22].

CHAPTER 7

ECONOMICS OF ADOPTING DC DISTRIBUTION

It is very important that DC distribution not only be technologically feasible but also be commercially feasible. A switch to DC from AC will not be possible without economic justification for the utility or customers. For new facilities which may be constructed with DC distribution, the new infrastructure costs would have to be taken into consideration. But, for existing facilities, the costs of upgrade must be weighed against the savings achieved through the lifetime.

7.1 Converter Costs

The most important cost when considering a system with DC distribution is the cost of the AC-DC converter which can convert the incoming power from the grid to DC. DC distribution will eliminate the costs of multiple conversions inside devices especially the ones which are backed by a UPS.

The other converter costs which must be considered are the costs of the DC-DC step down converter, used to reduce the distribution voltage from a few kV to more reasonable voltage levels which can be used in homes. High power DC-DC converters are expensive and these costs might outweigh the savings achieved through other loss reductions in DC systems. A comparison of the results of simulating the systems outlined in Appendices C through F shows a reduction in the line losses under DC. Utilities must consider whether these loss reductions would justify an overhaul of the system.

7.2 Overhead Line and Underground Cable Costs

In [20], the authors show how using AC cables and lines for DC power supply not only uses one less conductor, but we can actually transfer 1.15 times the power. This would lead to savings for utilities. This is a significant advantage especially in HVDC systems, where the long distances involved, mean using one less conductor results in significant savings.

The same is the case with distribution systems. In the simulations, for the DC systems, the neutral is eliminated and the return path is provided by a phase conductor. The elimination of two conductors leads to savings. For new distribution systems this would require less investment. For existing systems that are used for DC distribution, the existing conductors can be reconfigured into a three wire DC or four wire DC as shown in section 5.6.

7.3 Integration of Distributed Generation

Potentially, the biggest cost justification for shifting to DC comes from the possibilities of integrating distributed sources of electricity. PV technology is expected to reach grid parity in the near future and increased efficiencies due to direct integration into a DC network can prove to be a deciding factor in shifting the balance in favor of photovoltaics. However the efficiency of a charge control device will still be a factor to be taken into consideration.

7.4 Public Policy

A very important factor that can help in the adoption of DC distribution systems in appropriate public policy which grants federal subsidies to utilities that take efforts towards constructing high efficiency DC systems.

Federal subsidies are already offered to renewable energy technologies and this has greatly contributed to their adoption. For example, photovoltaic panel installation is eligible for a maximum of 25% subsidy to offset costs [23]. Similar subsidies can offer incentive to the utilities to invest in DC distribution systems.

As DC distribution is ultimately advantageous for renewable energy sources, most notably photovoltaics and to a smaller extent for fuel cells, federal subsidies can be clubbed together to create value for the government, the utility and the customers. If we assume a conservative federal subsidy rate of 15%, the savings are substantial and offer incentives for adopting DC distribution, especially for specialized businesses like data centers.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

The work performed in this thesis focused on carrying out a preliminary analysis of DC distribution systems. Two systems, based on the IEEE 13-node test feeder and the IEEE 37-node test feeder, were simulated. Approximate systems based on the simulated systems were simulated under DC power. The losses in each case are documented in Appendix C through Appendix F.

Various advantages of adopting DC distribution were explored along with issues like appliance integration and system protection. Some of the economic factors which may influence the adoption of DC distribution were explained.

The costs associated with the power electronic equipment needed for DC distribution make this technology unfeasible at this time. The preliminary results obtained from the simulations point towards higher efficiencies in DC distribution systems. The simulations need to be further refined by using additional device models such as DC-DC converters and distributed energy resources. This will provide a better picture of the advantages and disadvantages of DC distribution.

APPENDIX A

THE IEEE 13 NODE TEST FEEDER

The IEEE 13 Node Test Feeder is one of four standard distribution models developed by the IEEE Power Engineering Society's Power System Analysis, Computing and Economics Committee. This test feeder has several key distribution system components such as overhead lines, underground cables, spot loads, distributed loads, capacitors, transformers and regulators. It is very indicative of the types of distribution systems in use today and is a standard test system. Figure A.1 gives the layout of the 13 node system.

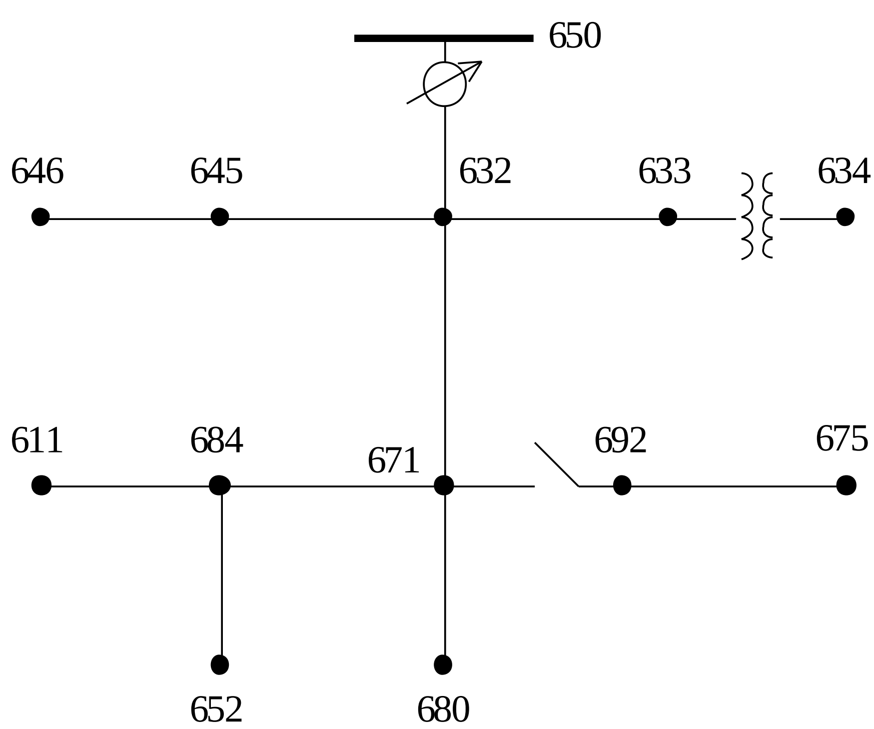


Figure A.1: Layout of the IEEE 13 node test feeder

TABLE A.1: Overhead line configuration data

Configuration	Phasing	Phase	Neutral	Spacing ID
		ACSR	ACSR	
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

TABLE A.2: Underground cable configuration data

Configuration	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

TABLE A.3: Transformer data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Table A.4: Capacitor data

Node	Phase-A (kVAr)	Phase-B (kVAr)	Phase-C (kVAr)
675	200	200	200
611	0	0	100
Total	200	200	300

Table A.5: Line segment data

Node A	Node B	Length (ft.)	Configuration
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Table A.6: Regulator Data

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	50		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Voltage Level:	122	122	122

Table A.6: Spot Load Data

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Table A.7: Distributed Load Data

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

APPENDIX B

THE IEEE 37 NODE TEST FEEDER

The IEEE 37 Node Test Feeder is one of four standard distribution models developed by the IEEE Power Engineering Society's Power System Analysis, Computing and Economics Committee. This test feeder has only underground cables and gives a standard to test underground distribution systems, which are a characteristic of dense urban areas. Figure B.1 gives the layout of the 37 node test feeder.

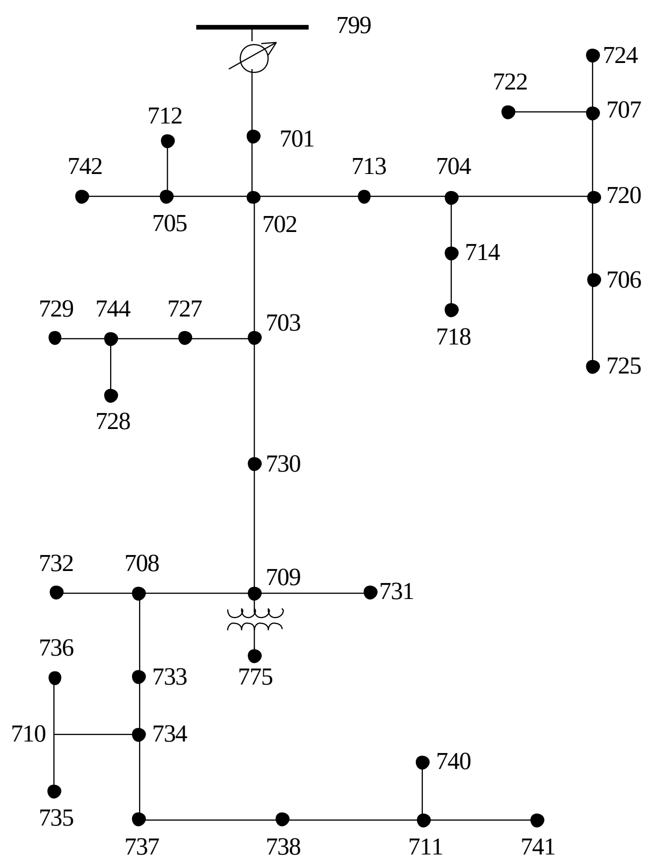


Figure B.1: Layout of the IEEE 37 node test feeder

Table B.1: Line segment data

Node A	Node B	Length(ft.)	Configuration
701	702	960	722
702	705	400	724
702	713	360	723
702	703	1320	722
703	727	240	724
703	730	600	723
704	714	80	724
704	720	800	723
705	742	320	724
705	712	240	724
706	725	280	724
707	724	760	724
707	722	120	724
708	733	320	723
708	732	320	724
709	731	600	723
709	708	320	723
710	735	200	724
710	736	1280	724
711	741	400	723
711	740	200	724
713	704	520	723
714	718	520	724
720	707	920	724
720	706	600	723
727	744	280	723
730	709	200	723
733	734	560	723
734	737	640	723
734	710	520	724
737	738	400	723
738	711	400	723
744	728	200	724
744	729	280	724
775	709	0	XFM-1
799	701	1850	721

Table B.2: Underground cable configurations

Configuration	Phasing	Cable	Spacing ID
721	A B C	1,000,000 AA, CN	515
722	A B C	500,000 AA, CN	515
723	A B C	2/0 AA, CN	515
724	A B C	#2 AA, CN	515

Table B.3: Regulator Data

Regulator ID	1	
Line Segment:	799- 701	
Location:	799	
Phases:	A - B -C	
Connection:	AB - CB	
Monitoring Phase:	AB & CB	
Bandwidth:	2.0 volts	
PT Ratio:	40	
Primary CT Rating:	350	
Compensator Settings:	Ph-AB	Ph-CB
R - Setting:	1.5	1.5
X - Setting:	3	3
Voltage Level:	122	122

TABLE B.4: Transformer data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2,500	230 - D	4.8 D	2	8
XFM -1	500	4.8 – D	0.48 – D	0.09	1.81

Table B.5: Spot Load Data

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-4
	Model	kW	kVAr	kW	kVAr	kW	kVAr
701	D-PQ	140	70	140	70	350	175
712	D-PQ	0	0	0	0	85	40
713	D-PQ	0	0	0	0	85	40
714	D-I	17	8	21	10	0	0
718	D-Z	85	40	0	0	0	0
720	D-PQ	0	0	0	0	85	40
722	D-I	0	0	140	70	21	10
724	D-Z	0	0	42	21	0	0
725	D-PQ	0	0	42	21	0	0
727	D-PQ	0	0	0	0	42	21
728	D-PQ	42	21	42	21	42	21
729	D-I	42	21	0	0	0	0
730	D-Z	0	0	0	0	85	40
731	D-Z	0	0	85	40	0	0
732	D-PQ	0	0	0	0	42	21
733	D-I	85	40	0	0	0	0
734	D-PQ	0	0	0	0	42	21
735	D-PQ	0	0	0	0	85	40
736	D-Z	0	0	42	21	0	0
737	D-I	140	70	0	0	0	0
738	D-PQ	126	62	0	0	0	0
740	D-PQ	0	0	0	0	85	40
741	D-I	0	0	0	0	42	21
742	D-Z	8	4	85	40	0	0
744	D-PQ	42	21	0	0	0	0
Total		727	357	639	314	1091	530

APPENDIX C

SIMULATION OF SYSTEM BASED ON THE 13 NODE TEST FEEDER

The first system to be simulated is based on the IEEE 13 node feeder. Certain modifications are made keeping in mind the limitations of the simulation software and to ensure better correlation between the systems when simulated in AC and DC. The system is simulated in WinIGS and is shown in the figure below.

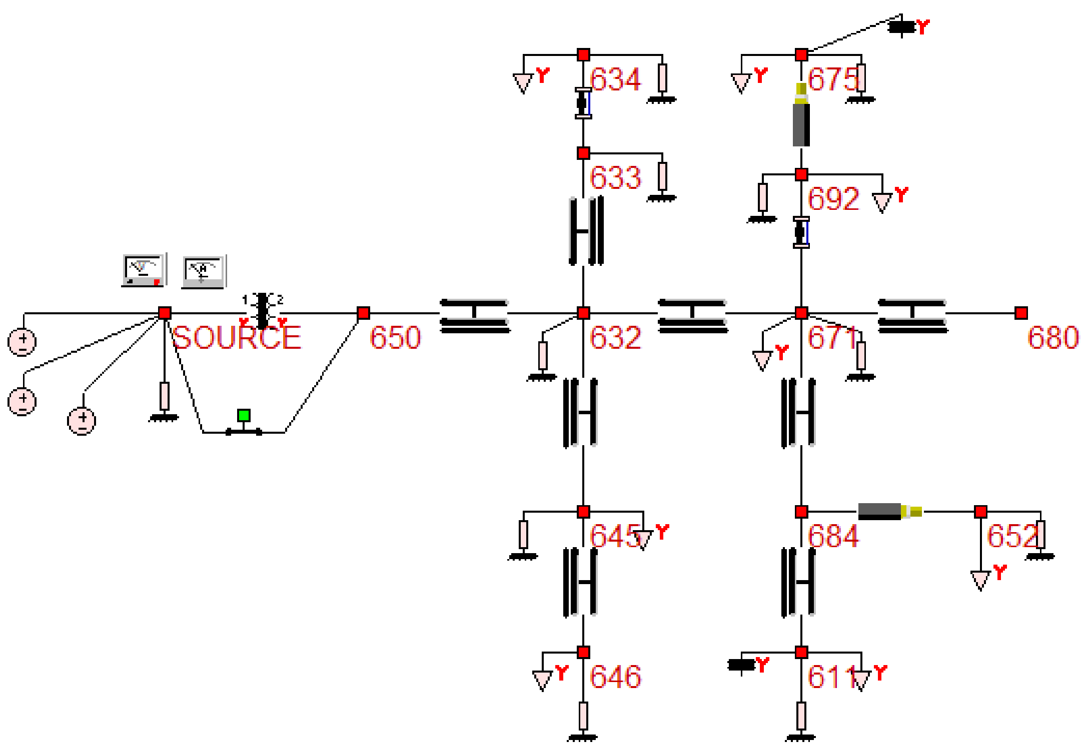


Figure C.1: System based on IEEE 13-bus feeder simulated on WinIGS

The following modifications are made to the 13 node system for the simulation:

- All loads are constant impedance spot loads
- The voltage regulator is not modeled along with the transformer between nodes 633-634
- The switch between nodes 671 and 692 is replaced by a bus connector
- The source is replaced by three single phase voltage sources

Table C.1: RMS node voltages

Node	Phase A (V)	Phase B (V)	Phase C (V)
650	2375.879	2375.879	2375.879
632	2354.666	2340.523	2347.595
633	2354.666	2340.523	2340.523
645	0	2333.452	2340.523
646	0	2333.452	2333.452
671	2333.452	2333.452	2326.381
692	2333.452	2333.452	2326.381
675	2319.31	2319.31	2312.239
684	2333.452	0	2326.381
611	0	0	2326.381
652	2326.381	0	0

Table C.2: RMS branch currents

From	To	Phase A (A)	Phase B (A)	Phase C (A)
650	632	181.0193	221.3244	238.295
632	633	26.65793	26.23366	26.23366
632	645	0	63.92245	65.5488
645	646	0	35.63818	35.70889
632	671	155.5635	133.9967	154.1493
671	684	20.85965	0	27.93072
684	652	21.14249	0	0
684	611	0	0	27.93072
692	675	65.61951	64.84169	64.84169

Table C.3: Line losses

From Node	To Node	Loss in Phase A (W)	Loss in Phase B (W)	Loss in Phase C (W)
650	632	6630.4	12379.15	14086.6
632	633	55.6075	55.279	57.6905
632	645	0	517.54	444.4965
645	646	0	96.768	81.305
632	671	5379	4244.8	5820.6
671	684	29.9425	0	53.9175
684	652	103.753	0	0
684	611	0	0	53.5225
692	675	914.08	935.34	930.755
Total Loss (W)		13113	18229	21529
		52871		

APPENDIX D

SIMULATION OF SYSTEM BASED ON THE 37 NODE TEST FEEDER

The second system to be simulated is based on the IEEE 37 node feeder. Software model limitations require that the system be modified but efforts have been made to ensure that the modifications are minimal and the system remains a fair representation of the 37 node feeder. The system is simulated in WinIGS and is shown in the figure below.

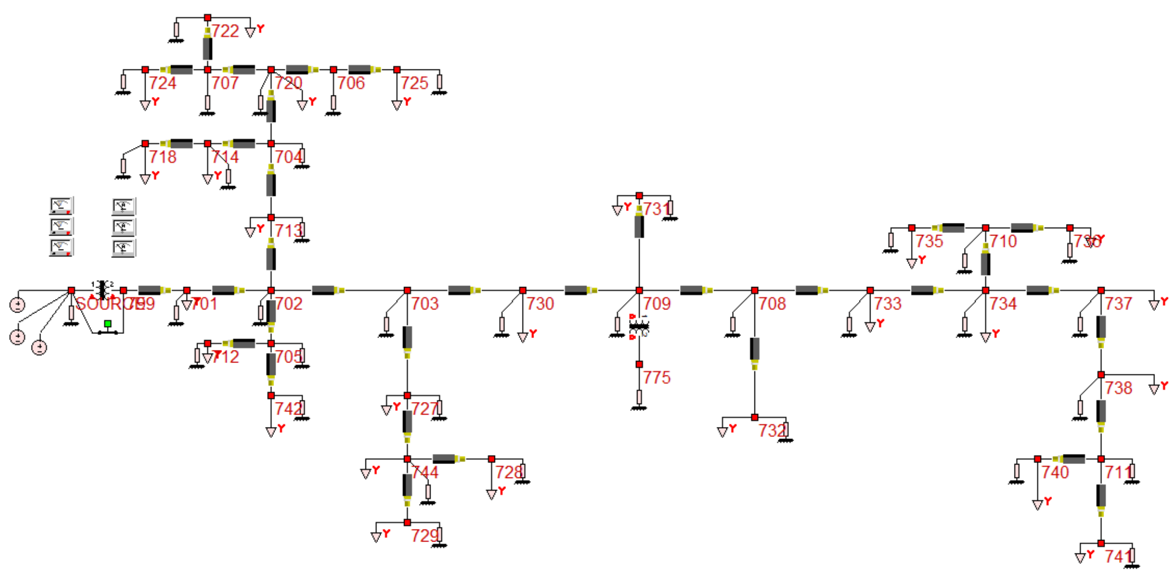


Figure D.1: System based on IEEE 37-bus feeder simulated on WinIGS

The following modifications are made to the 37 node system for the simulation:

- All distributed loads are modeled as spot loads
- The voltage regulator between nodes 799 and 701 is not modeled

- The source is modeled as three single phase voltage sources
- Loads are distributed equally over all three phases and connected in Y

Table D.1: RMS node voltages

Node	Phase A (V)	Phase B (V)	Phase C (V)
799	2672.86	2672.86	2672.86
701	2573.87	2573.87	2573.87
702	2524.37	2524.37	2524.37
705	2517.3	2517.3	2517.3
712	2510.23	2503.16	2510.23
742	2510.23	2510.23	2510.23
713	2517.3	2517.3	2517.3
704	2503.16	2503.16	2524.37
714	2503.16	2503.16	2503.16
718	2503.16	2503.16	2503.16
720	2496.09	2496.09	2496.09
706	2496.09	2496.09	2510.23
725	2489.02	2489.02	2489.02
707	2481.94	2481.94	2481.94
724	2474.87	2474.87	2474.87
722	2481.94	2481.94	2481.94
703	2481.94	2481.94	2481.94
727	2474.87	2474.87	2474.87
744	2474.87	2474.87	2474.87
728	2474.87	2474.87	2474.87
729	2474.87	2474.87	2474.87
730	2453.66	2453.66	2453.66
709	2446.59	2446.59	2446.59
731	2446.59	2446.59	2446.59

Table D.1 continued

Node	Phase A (V)	Phase B (V)	Phase C (V)
708	2439.52	2439.52	2439.52
732	2432.45	2432.45	2432.45
733	2425.38	2425.38	2425.38
734	2411.23	2411.23	2411.23
710	2404.16	2404.16	2404.16
735	2404.16	2404.16	2404.16
736	2397.09	2397.09	2397.09
737	2397.09	2397.09	2397.09
738	2390.02	2390.02	2390.02
740	2390.02	2390.02	2390.02
711	2390.02	2390.02	2390.02
741	2390.02	2390.02	2390.02

Table D.2: RMS branch currents

From Node	To Node	Phase A (A)	Phase B (A)	Phase C (A)
799	701	236.880772	236.8807717	236.880772
701	702	193.040151	193.0401513	193.040151
702	705	120.066731	120.0667314	120.066731
705	712	10.2813326	10.27426153	10.2813326
705	742	10.2813326	10.2813326	10.2813326
702	713	52.8208766	52.39661249	53.5279833
713	704	42.1435642	42.14356416	42.1435642
704	714	12.7986327	12.79863274	12.7986327
714	718	10.217693	10.21769299	10.217693

Table D.2 continued

From Node	To Node	Phase A (A)	Phase B (A)	Phase C (A)
704	720	29.6984848	29.48635278	29.9813275
720	707	21.9910209	21.92031022	21.9203102
707	724	5.05581349	5.055813485	5.05581349
707	722	16.8998521	16.89985207	16.8998521
720	706	5.09823989	5.084097757	5.11238203
706	725	5.09116882	5.091168825	5.09116882
702	703	15.1320851	15.13208512	15.1320851
703	727	20.2232539	20.22325394	20.2232539
727	744	15.2027958	15.13208512	15.1320851
744	728	5.06288455	5.062884553	5.06288455
744	729	5.06288455	5.055813485	5.05581349
703	730	99.9141882	99.91418818	99.9141882
730	709	90.4389573	89.94398257	91.4996175
709	731	9.98434775	9.991418818	9.98434775
709	708	79.973777	79.97377695	79.973777
708	732	5.05581349	5.055813485	5.05581349
708	733	75.0240295	75.02402948	75.0240295
733	734	65.1245345	65.12453455	65.1245345
734	710	14.707821	14.70782105	14.707821
710	735	9.98434775	9.991418818	9.98434775
710	736	4.90024999	4.900249994	4.90024999
734	737	45.6790981	45.53767671	45.7498087
737	738	29.2035101	29.20351006	29.2035101
738	711	14.6371104	14.63711037	14.6371104

Table D.2 continued

From Node	To Node	Phase A (A)	Phase B (A)	Phase C (A)
711	740	9.77221572	9.772215716	9.77221572
711	741	4.87903679	4.87903679	4.87903679

Table D.3: Line losses

From Node	To Node	Loss in Phase A (W)	Loss in Phase B (W)	Loss in Phase C (W)
799	701	26582.3	26582.3	26582.3
701	702	10101	10101	10101
702	705	789.57	789.57	789.57
705	712	20.356	20.342	20.356
705	742	27.1898	27.1898	27.1898
702	713	462.767	459.05	468.962
713	704	428.822	428.822	428.822
704	714	10.498	10.498	10.498
714	718	43.639	43.639	43.639
704	720	324.87	322.55	327.964
720	707	356.095	354.95	354.95
707	724	15.587	15.587	15.587
707	722	27.485	27.485	27.485
720	706	7.21	7.19	7.23
706	725	5.76	5.76	5.76
702	703	676.24	676.24	676.24
703	727	78.793	78.793	78.793

Table D.3 continued

From Node	To Node	Loss in Phase A (W)	Loss in Phase B (W)	Loss in Phase C (W)
727	744	29.885	29.746	29.746
744	728	4.117	4.117	4.117
744	729	5.7638	5.75575	5.75575
703	730	2776.55	2776.55	2776.55
730	709	754.61	750.48	763.46
709	731	27.7458	27.7655	27.7458
709	708	949.475	949.475	949.475
708	732	6.47075	6.47075	6.47075
708	733	835.538	835.538	835.538
733	734	1100.6	1100.6	1100.6
734	710	90.272	90.272	90.272
710	735	15.7438	15.755	15.7438
710	736	24.6362	24.6362	24.6362
734	737	617.576	615.664	618.532
737	738	158.386	158.386	158.386
738	711	39.744	39.744	39.744
711	740	15.3402	15.3402	15.3402
711	741	4.416	4.416	4.416
Total Loss (W)		47415	47401.6	47432.8
		142249		

APPENDIX E
APPROXIMATE 13 NODE SYSTEM UNDER DC

The system based on the 13 node feeder is simulated using a converter. A six-pulse converter converts the incoming AC voltage into DC which is then used to serve the loads. The three phase lines and neutral are replaced by two lines which are the resistive equivalent models of the phase conductors. Loads in this DC system are to be connected between two phase conductors in the AC system. The figure below shows the system without using resistive equivalents.

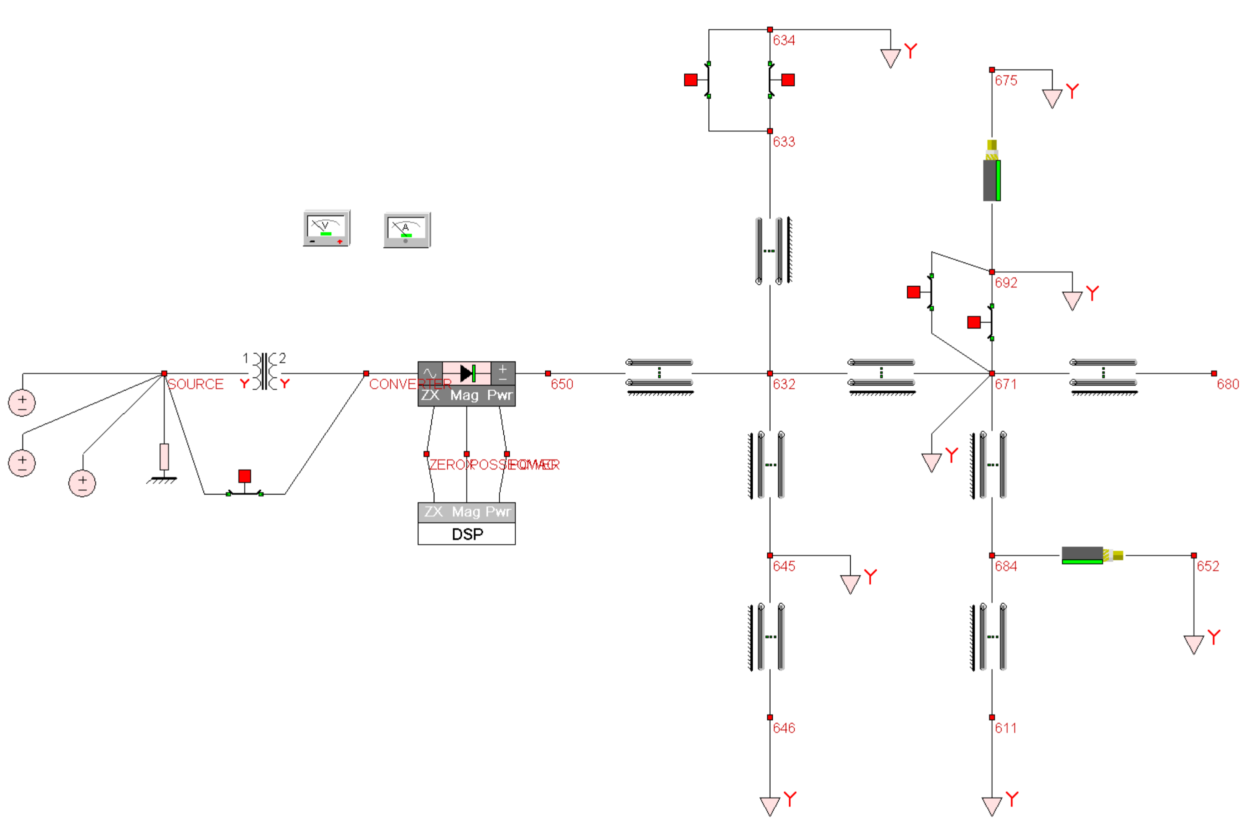


Figure E.1: System based on 13 node feeder under DC without resistive equivalents

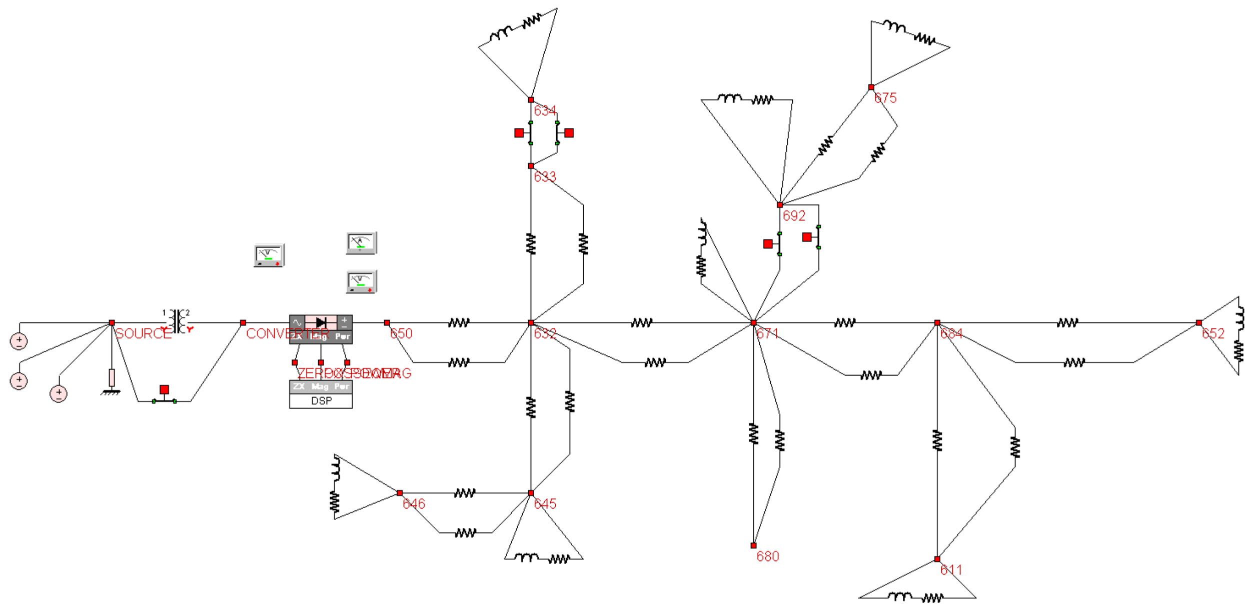


Figure E.2: System based on 13 node feeder with six-pulse converter

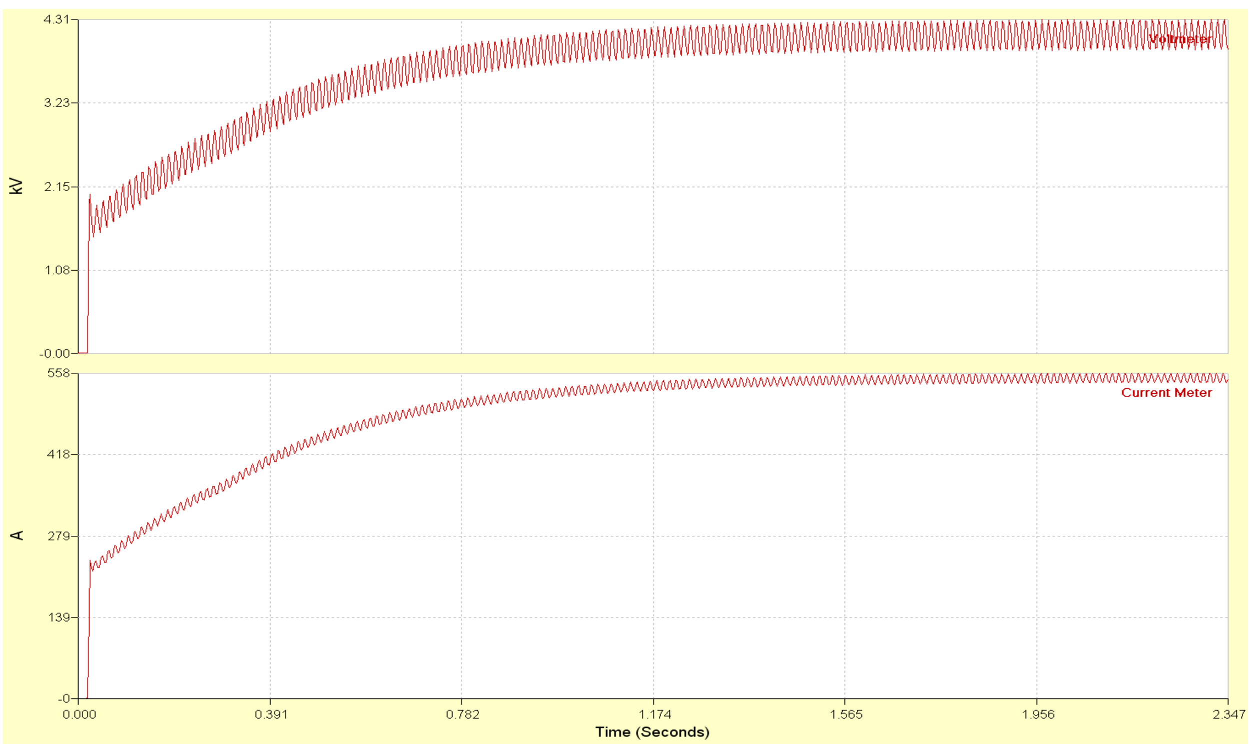


Figure E.3: Voltage and current at node 650

Table E.1: Node line to node neutral voltages

Node	Voltage (V)
650	4120
632	4039
633	4033
634	4033
645	4012
646	4003
671	3988
692	3988
675	3978
680	3988
684	3977
611	3971
652	3964

Table E.2: Branch currents

To Node	From Node	Current (A)
650	632	550
632	633	54.912
632	645	13.94
645	646	4.5
632	671	25.62
692	675	132.77
671	684	90.2
684	611	47.6
684	652	42.6

Table E.3: Line losses

To Node	From Node	Losses (W)
650	632	21285
632	633	169.019
632	645	1831.72
645	646	318.15
632	671	9323.12
692	675	685.757
671	684	517.748
684	611	144.323
684	652	267.102
Total Losses (W)		34541.9

APPENDIX F

APPROXIMATE 37 NODE SYSTEM UNDER DC

The system based on the 37 node feeder is simulated using a converter. A six-pulse converter converts the incoming AC voltage into DC which is then used to serve the loads. The three phase lines and neutral are replaced by two lines which are the resistive equivalent models of the phase conductors. Loads in this DC system are to be connected between two phase conductors in the AC system. The figure below shows the system.

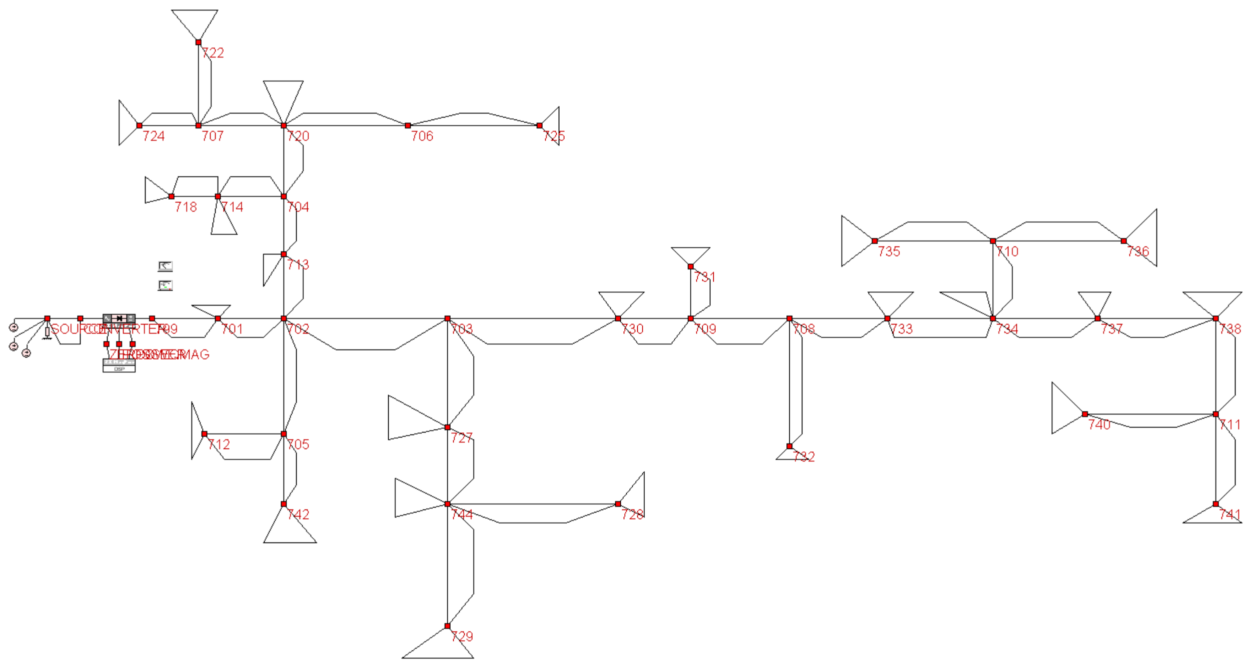


Figure F.1: Simulated system based on the 37 node feeder with six pulse converter

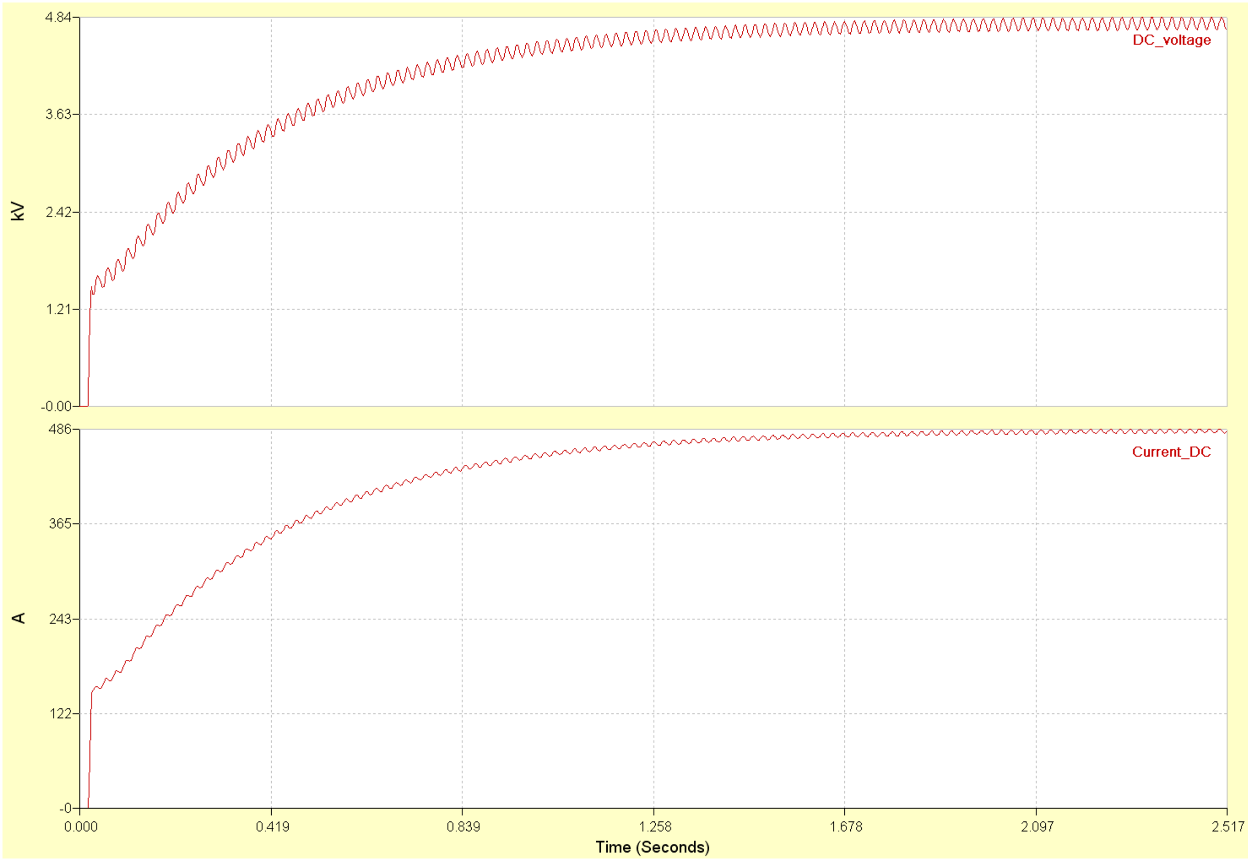


Figure F.2: Voltage and current at node 799

Table F.1: Node line to node neutral voltages

Node	Voltage (V)
799	4750
701	4710
702	4681
703	4656
704	4656
705	4671
706	4640
707	4618
708	4596

Table F.1 continued

Node	Voltage (V)
709	4611
710	4552
711	4537
712	4668
713	4670
714	4655
718	4649
720	4642
722	4615
724	4613
725	4639
727	4650
728	4646
729	4646
730	4621
731	4607
732	4594
733	4582
734	4562
735	4550
736	4544
737	4546
738	4540
740	4535
741	4524
742	4665
744	4644

Table F.2: Branch currents

From Node	To Node	Current (A)
701	702	402
702	703	252
702	705	42
702	713	108.5
703	727	42.32
703	730	209.6
704	714	26.14
704	720	61.3
705	712	21.03
705	742	21.03
706	725	10.56
707	722	35.03
707	724	10.51
708	732	10.45
708	733	157.7
709	708	168.1
709	731	20.74
710	735	20.46
710	736	10.33
711	740	20.38
711	741	10.3
713	704	87.4
714	718	20.94
720	706	10.56
720	707	45.5
727	744	31.74
730	709	188.8
733	734	137

Table F.2 continued

From Node	To Node	Current (A)
734	710	30.8
734	737	95.9
737	738	61.44
738	711	30.68
744	728	10.58
744	729	10.58
799	701	492

Table F.3: Line losses

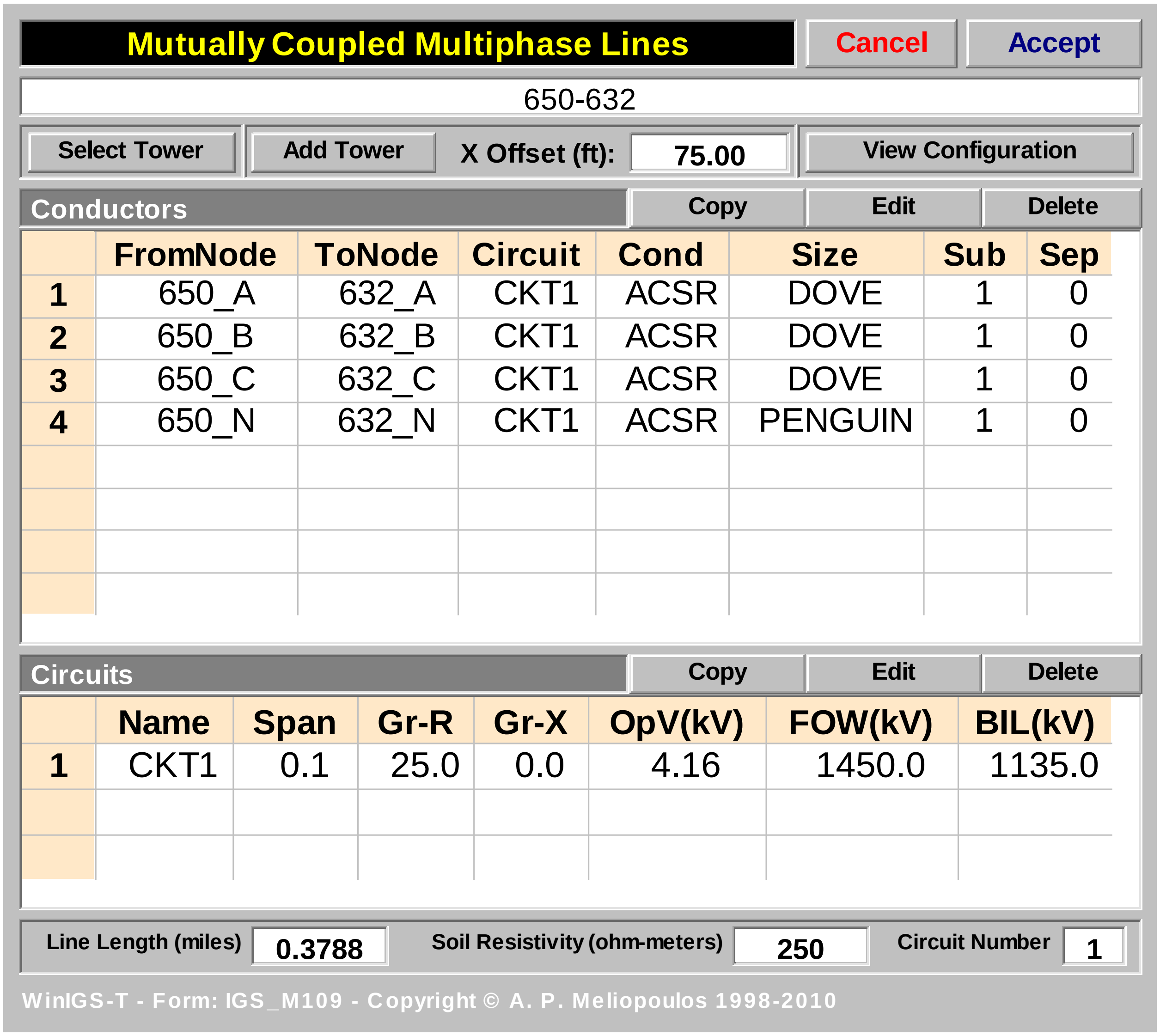
From Node	To Node	Losses (W)
701	702	6058.14
702	703	3270.96
702	705	206.22
702	713	646.66
703	727	125.2672
703	730	3839.872
704	714	15.9454
704	720	437.682
705	712	30.95616
705	742	41.26086
706	725	9.11328
707	722	42.94678
707	724	24.47779
708	732	10.1992
708	733	1159.095

Table F.3 continued

From Node	To Node	Losses (W)
709	708	1316.223
709	731	37.58088
710	735	24.42924
710	736	39.85314
711	740	24.23182
711	741	6.18
713	704	578.588
714	718	66.50544
720	706	9.74688
720	707	556.01
727	744	41.07156
730	709	1038.4
733	734	1531.66
734	710	143.8668
734	737	857.346
737	738	219.89376
738	711	54.82516
744	728	6.52786
744	729	9.14112
799	701	8905.2
Total Losses (W)		31386.076

APPENDIX G

LINE CONFIGURATIONS AND DEVICE MODELS


Mutually Coupled Multiphase Lines

Cancel

Accept

650-632

Select Tower

Add Tower

X Offset (ft): 75.00

View Configuration

Conductors

Copy

Edit

Delete

	FromNode	ToNode	Circuit	Cond	Size	Sub	Sep
1	650_A	632_A	CKT1	ACSR	DOVE	1	0
2	650_B	632_B	CKT1	ACSR	DOVE	1	0
3	650_C	632_C	CKT1	ACSR	DOVE	1	0
4	650_N	632_N	CKT1	ACSR	PENGUIN	1	0

Circuits

Copy

Edit

Delete

	Name	Span	Gr-R	Gr-X	OpV(kV)	FOW(kV)	BIL(kV)
1	CKT1	0.1	25.0	0.0	4.16	1450.0	1135.0

Line Length (miles) 0.3788

Soil Resistivity (ohm-meters) 250

Circuit Number 1

WinIGS-T - Form: IGS_M109 - Copyright © A. P. Meliopoulos 1998-2010

Figure G.1: Conductor data for configuration 601

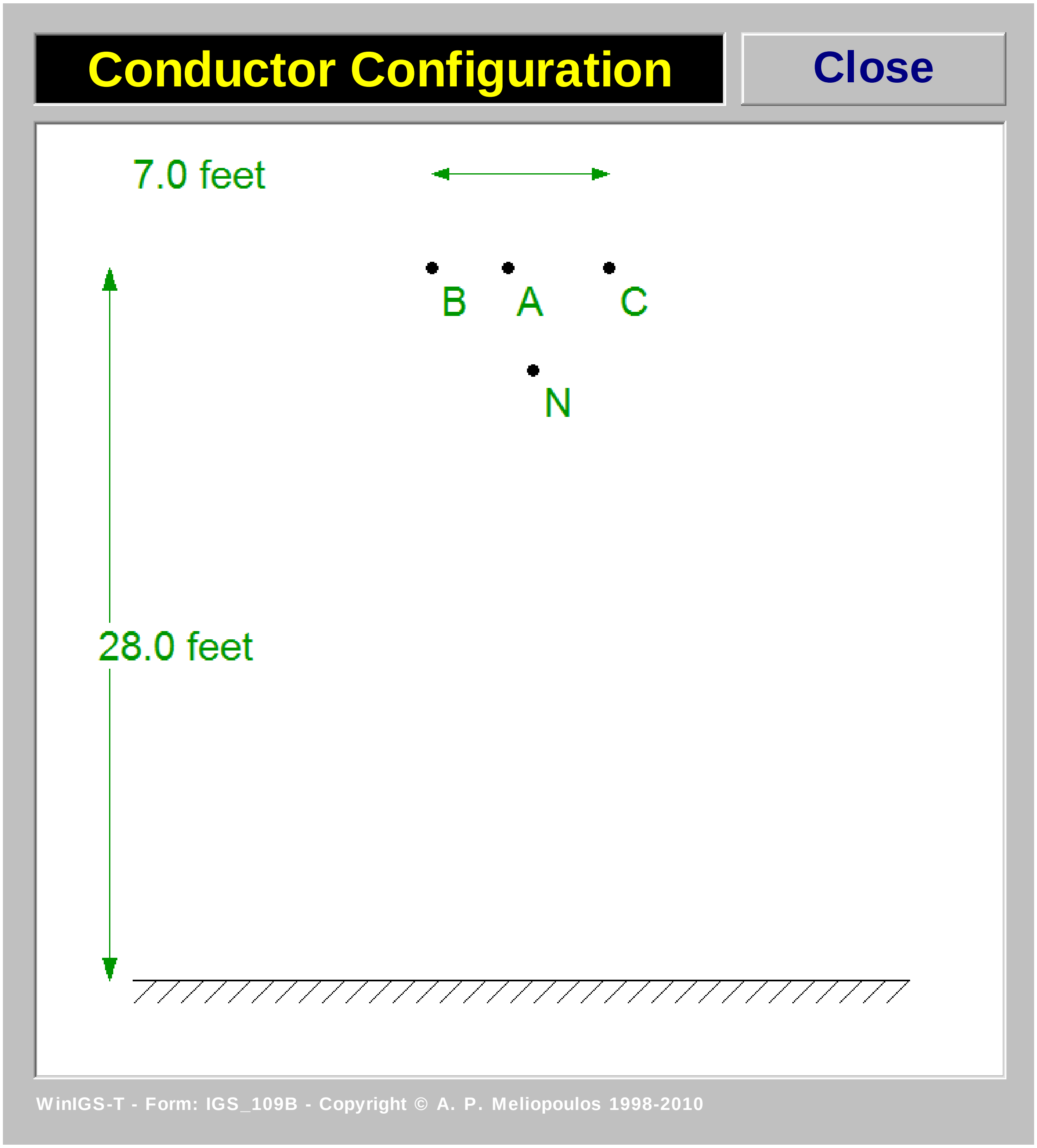
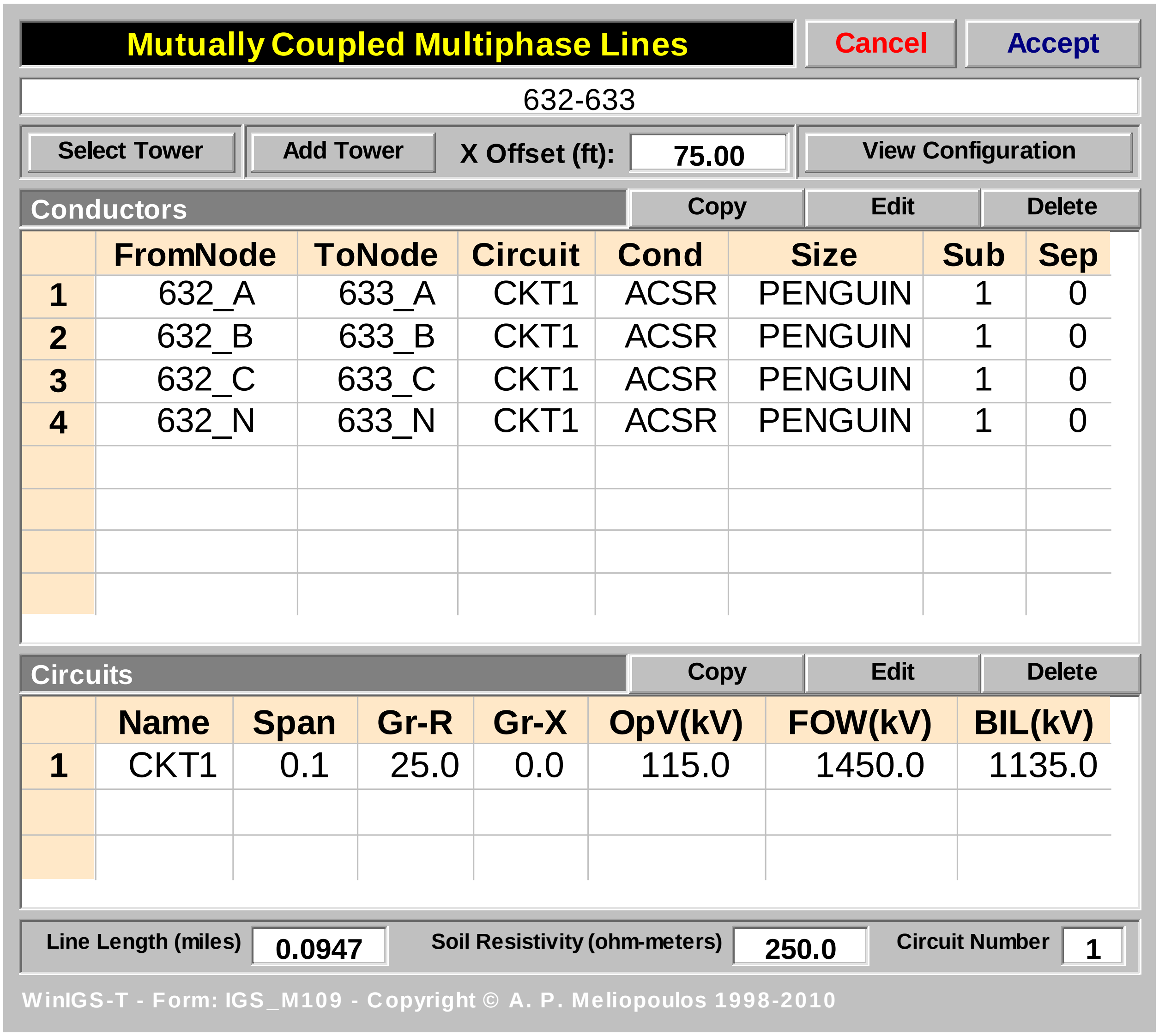


Figure G.2: Configuration 601


Mutually Coupled Multiphase Lines

Cancel | Accept

632-633

Select Tower | Add Tower | X Offset (ft): 75.00 | View Configuration

Conductors | Copy | Edit | Delete

	FromNode	ToNode	Circuit	Cond	Size	Sub	Sep
1	632_A	633_A	CKT1	ACSR	PENGUIN	1	0
2	632_B	633_B	CKT1	ACSR	PENGUIN	1	0
3	632_C	633_C	CKT1	ACSR	PENGUIN	1	0
4	632_N	633_N	CKT1	ACSR	PENGUIN	1	0

Circuits | Copy | Edit | Delete

	Name	Span	Gr-R	Gr-X	OpV(kV)	FOW(kV)	BIL(kV)
1	CKT1	0.1	25.0	0.0	115.0	1450.0	1135.0

Line Length (miles) 0.0947 | Soil Resistivity (ohm-meters) 250.0 | Circuit Number 1

WinIGS-T - Form: IGS_M109 - Copyright © A. P. Meliopoulos 1998-2010

Figure G.3: Conductor data for configuration 602

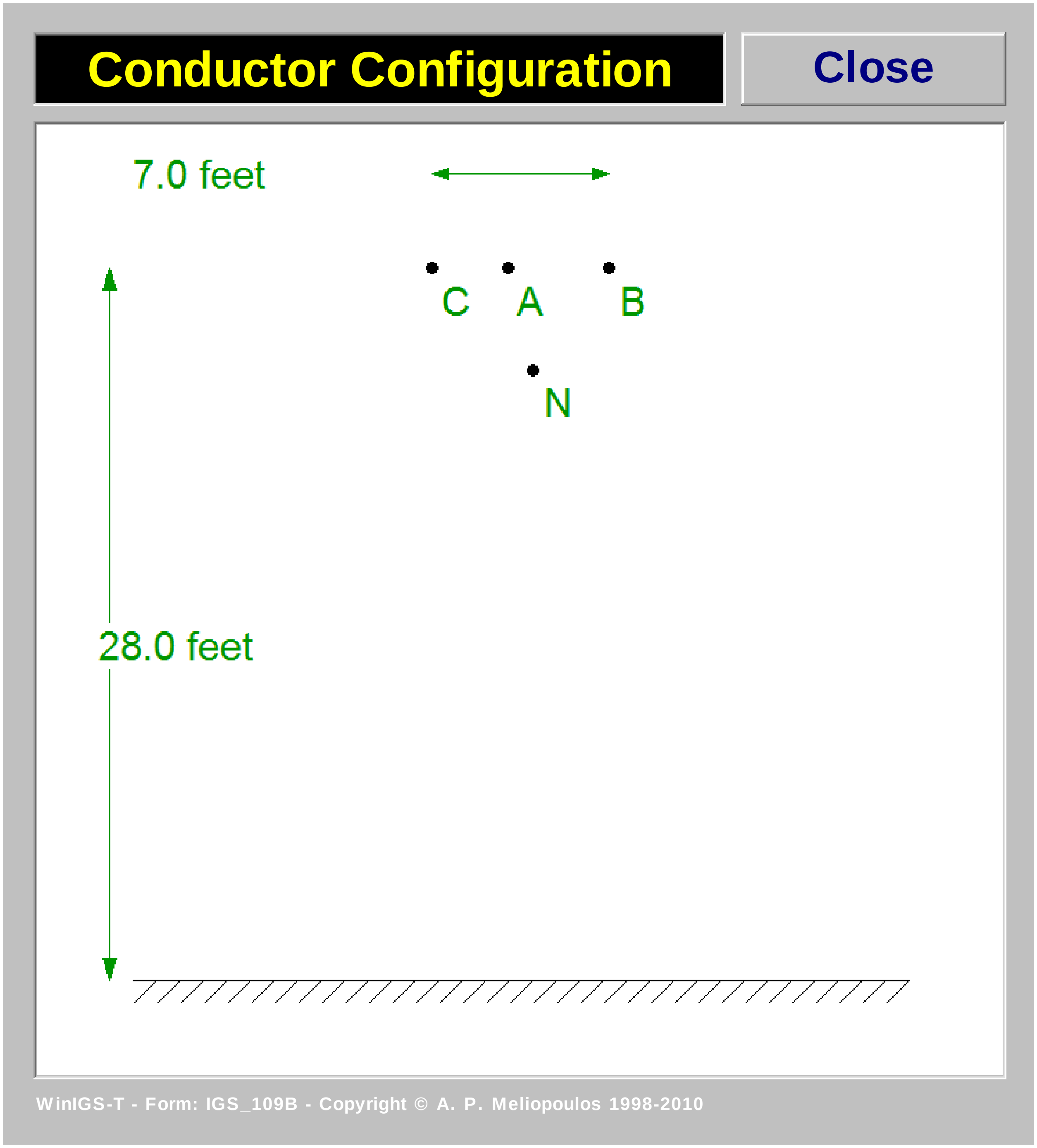


Figure G.4: Configuration 602

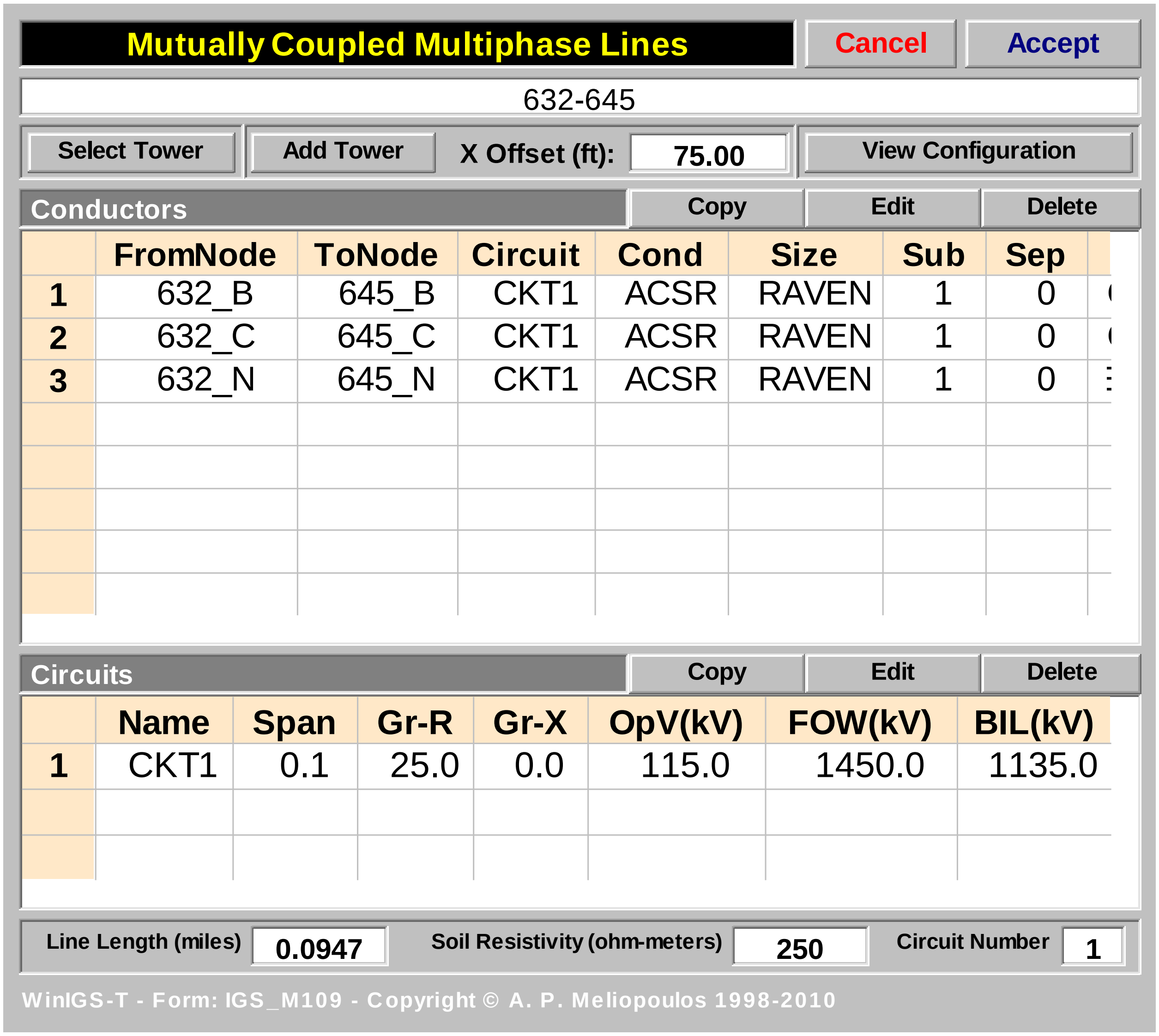


Figure G.5: Conductor data for configuration 603

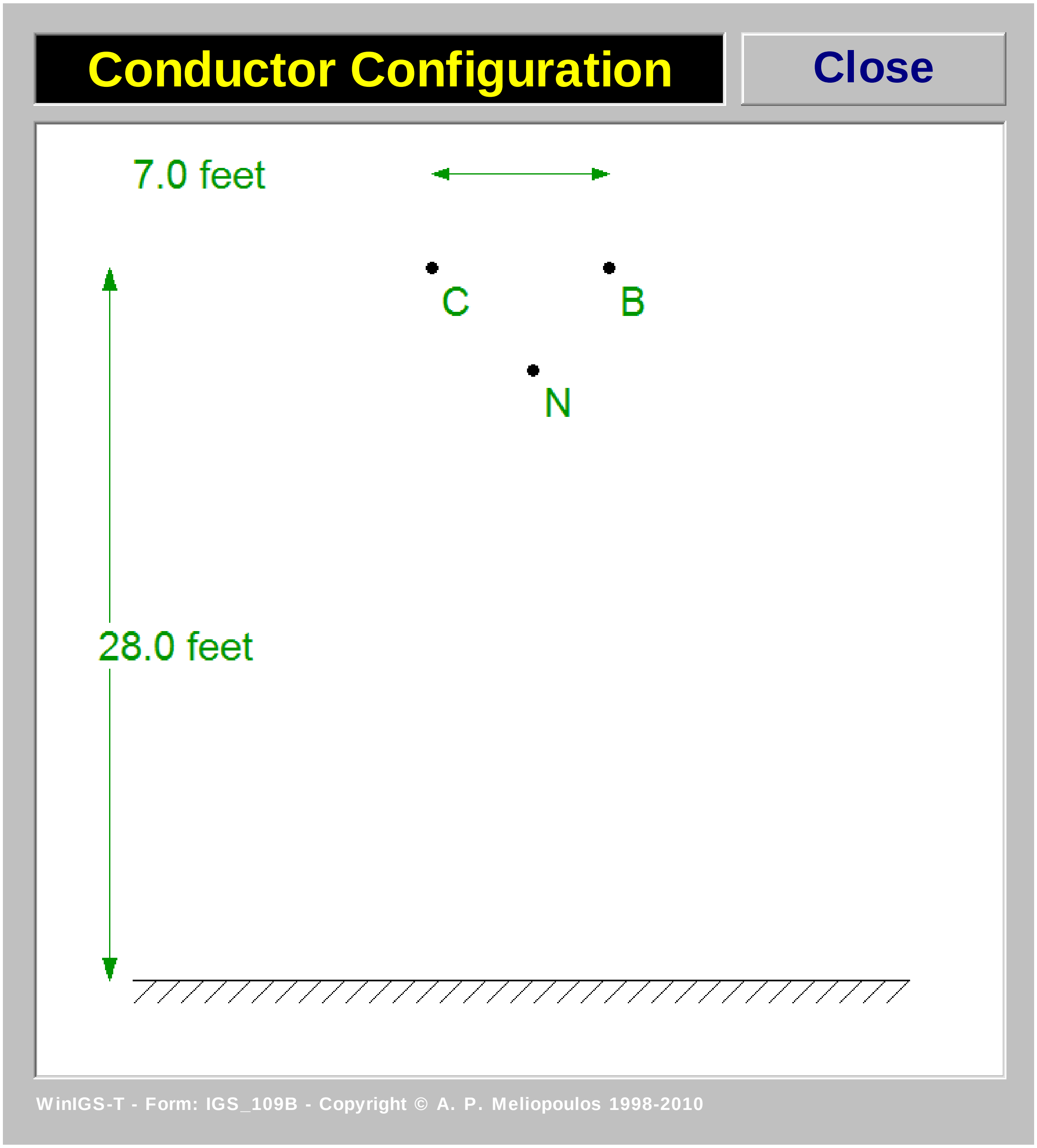


Figure G.6: Configuration 603

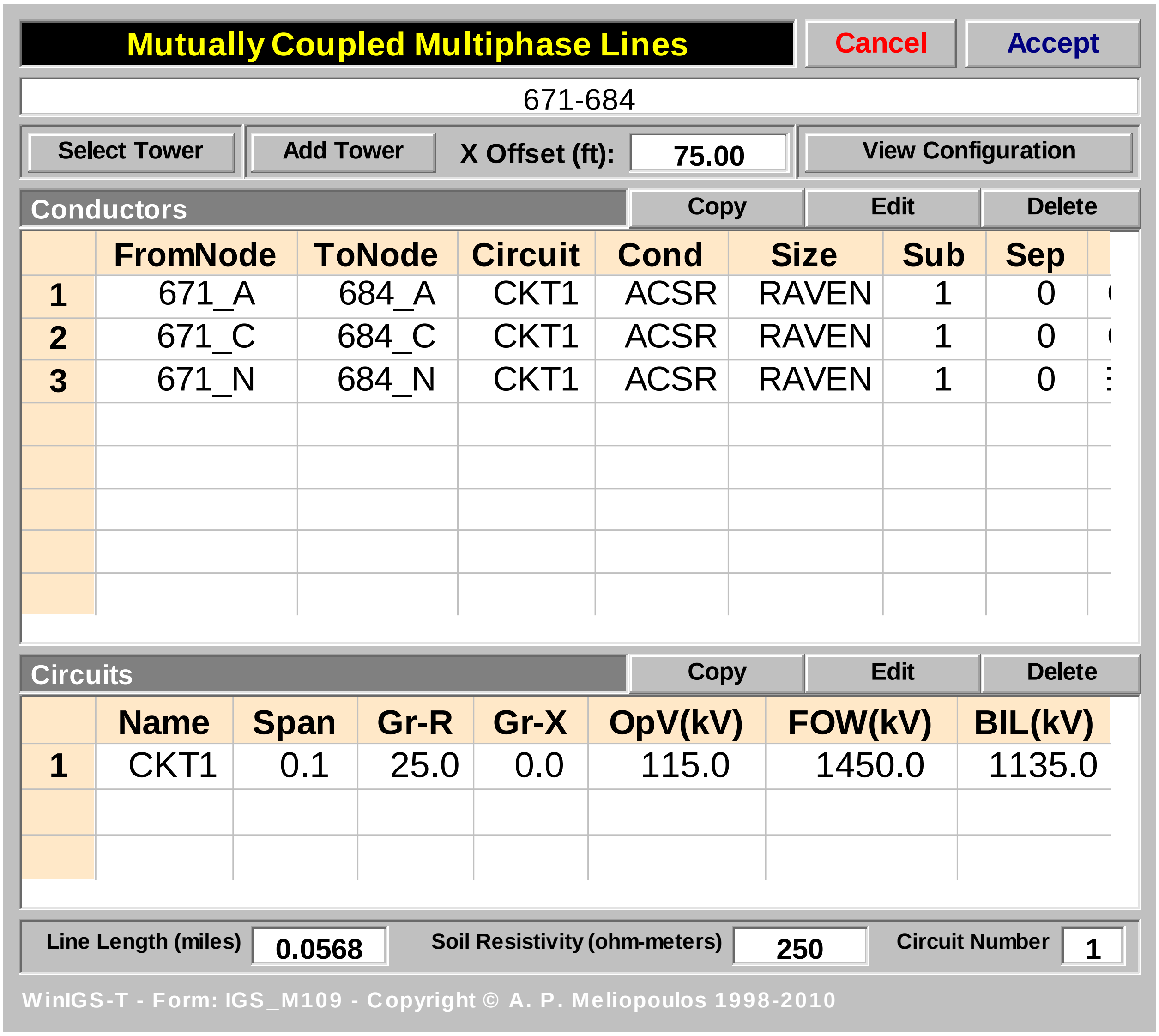


Figure G.7: Conductor data for configuration 604

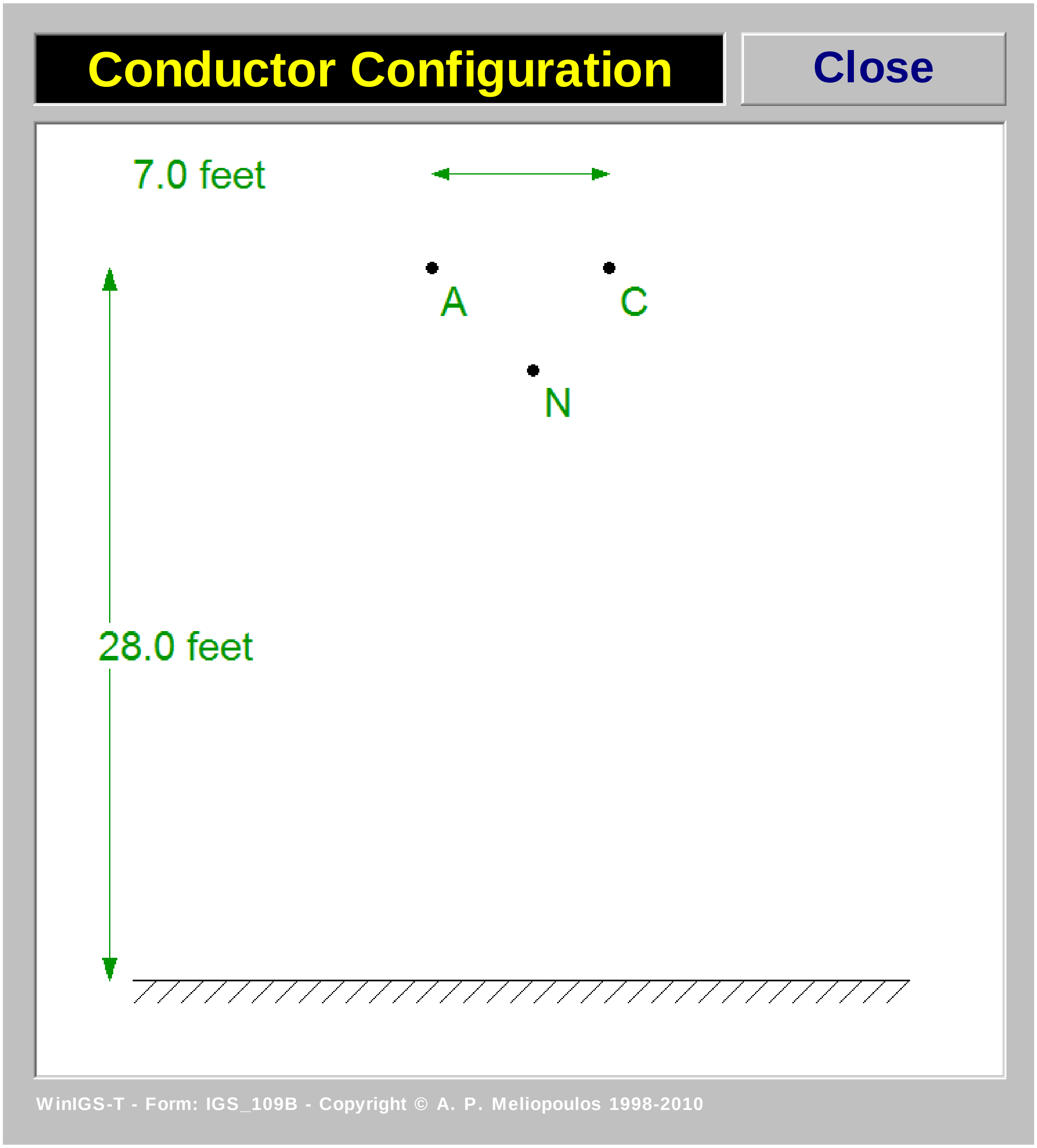


Figure G.8: Configuration 604

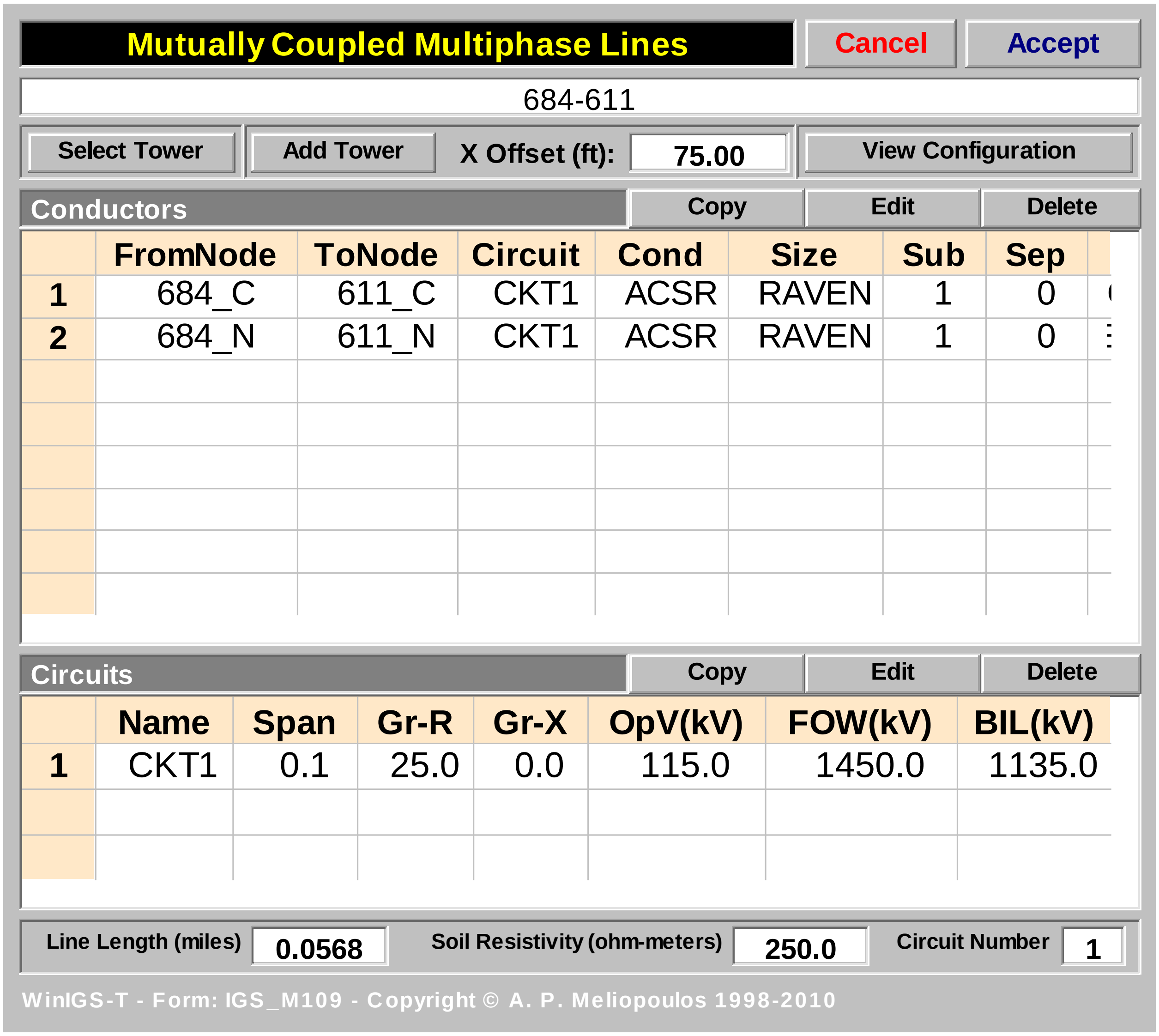


Figure G.9: Conductor data for configuration 605

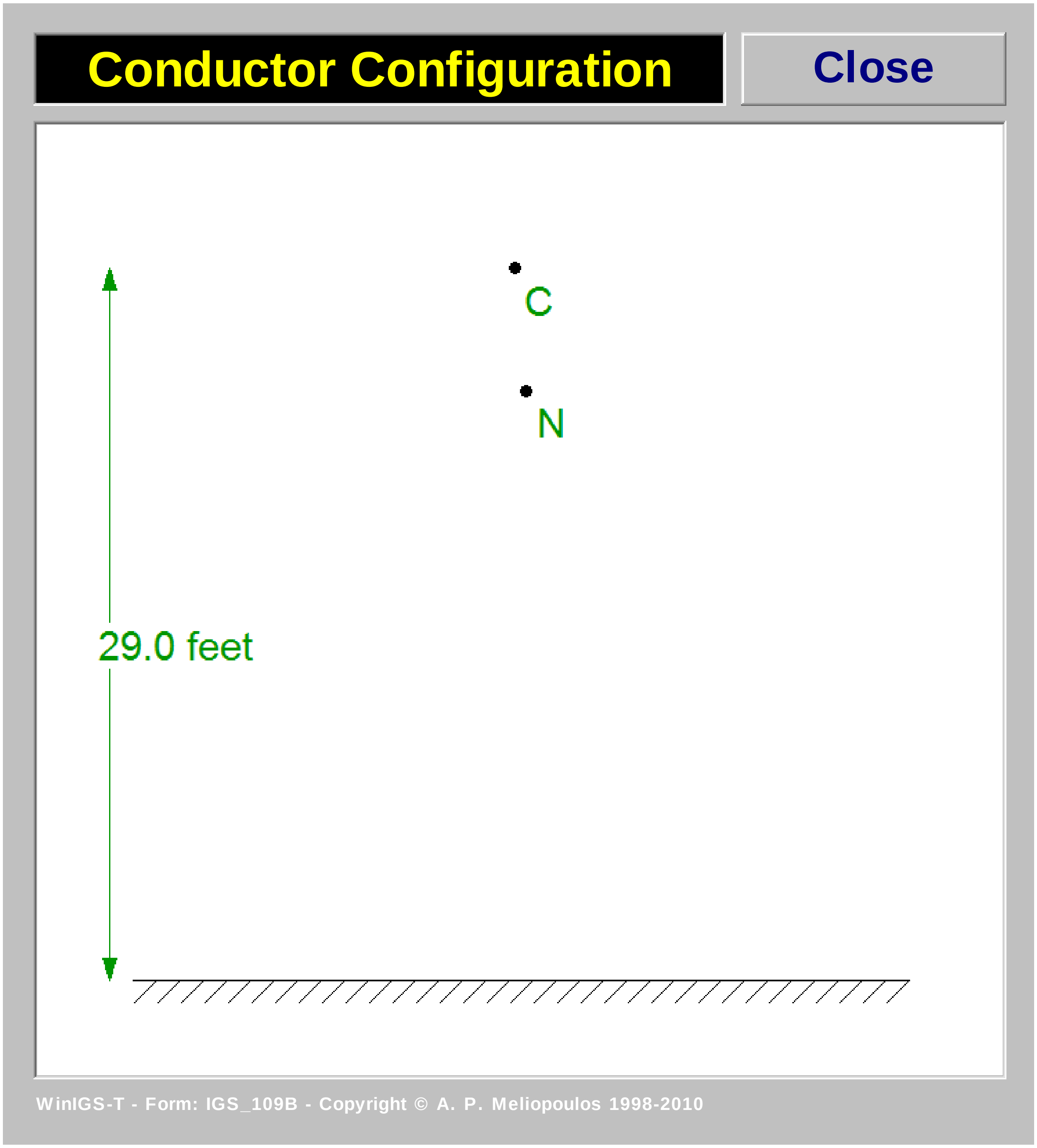


Figure G.10: Configuration 605

Figure G.11: Configuration 606

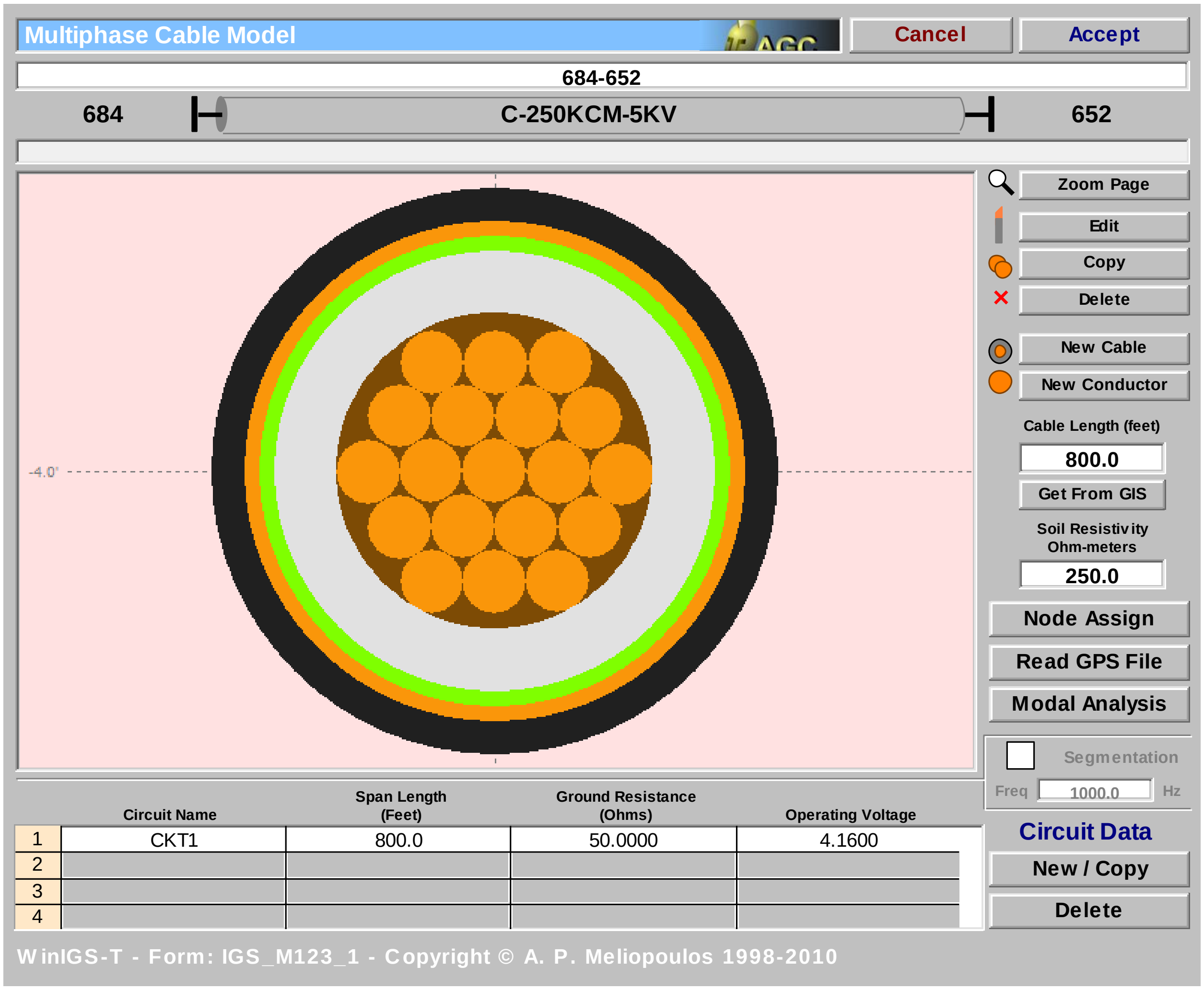


Figure G.12: Configuration 607

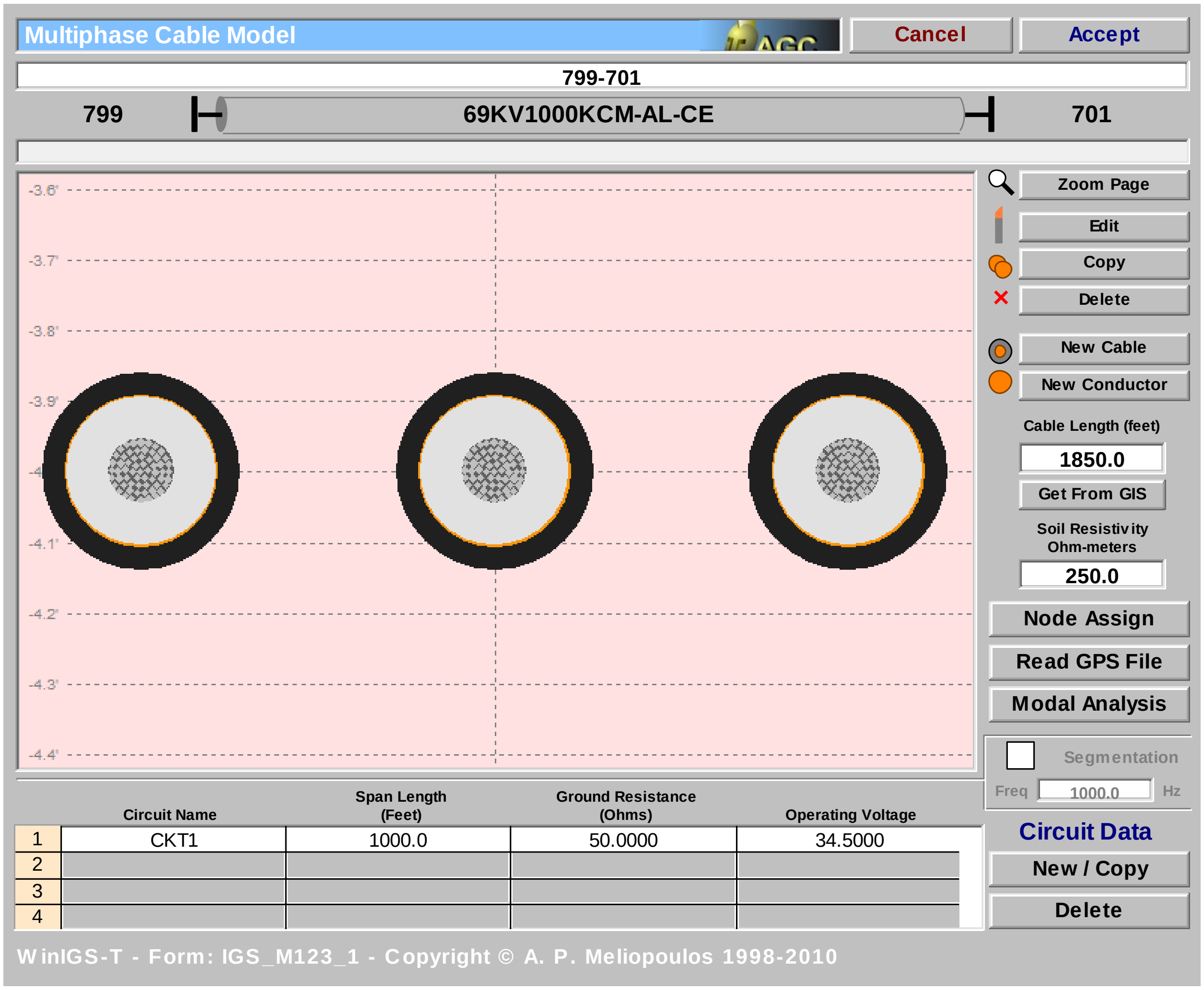
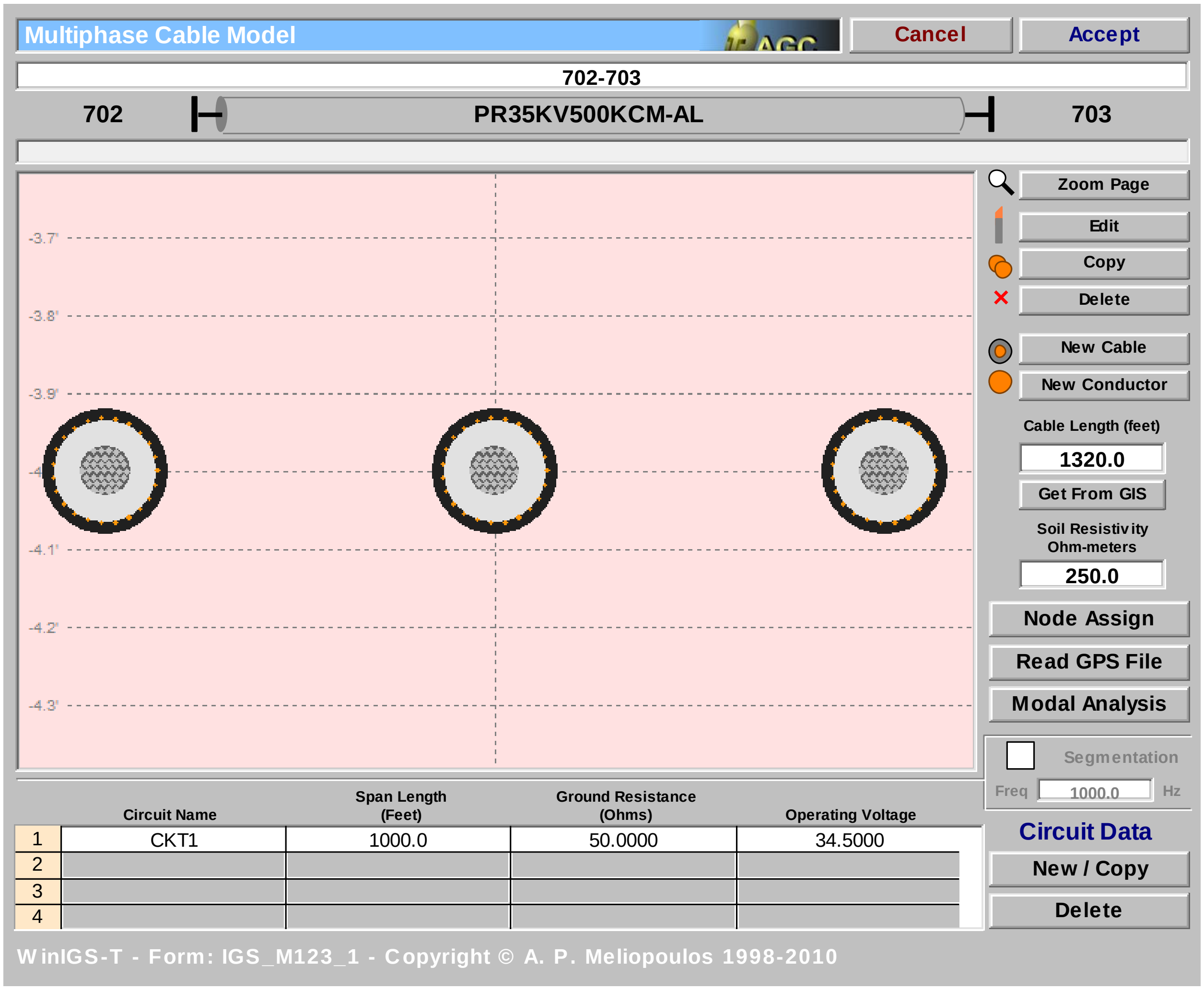


Figure G.13: Configuration 721



	Circuit Name	Span Length (Feet)	Ground Resistance (Ohms)	Operating Voltage
1	CKT1	1000.0	50.0000	34.5000
2				
3				
4				

Figure G.14: Configuration 722

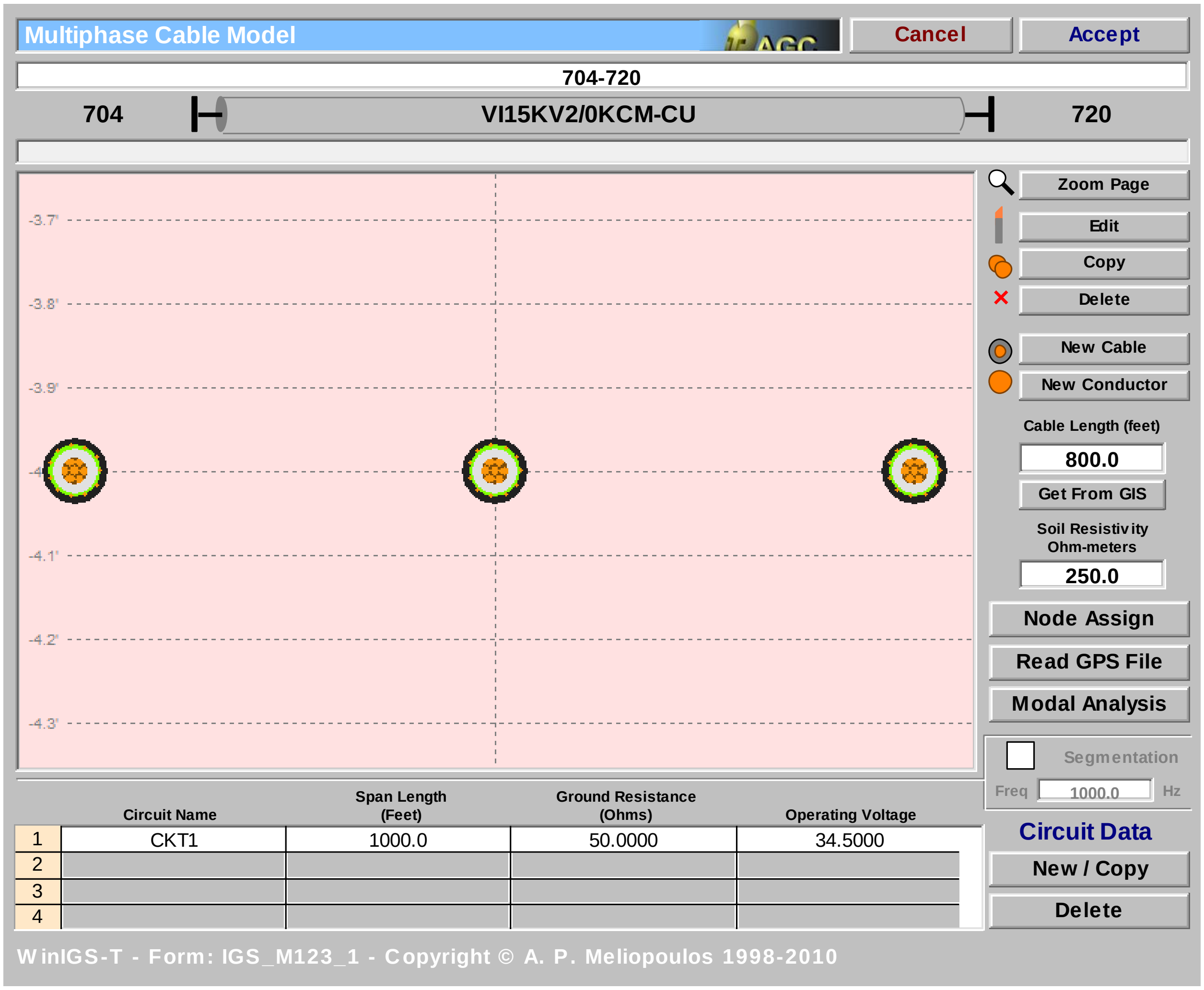
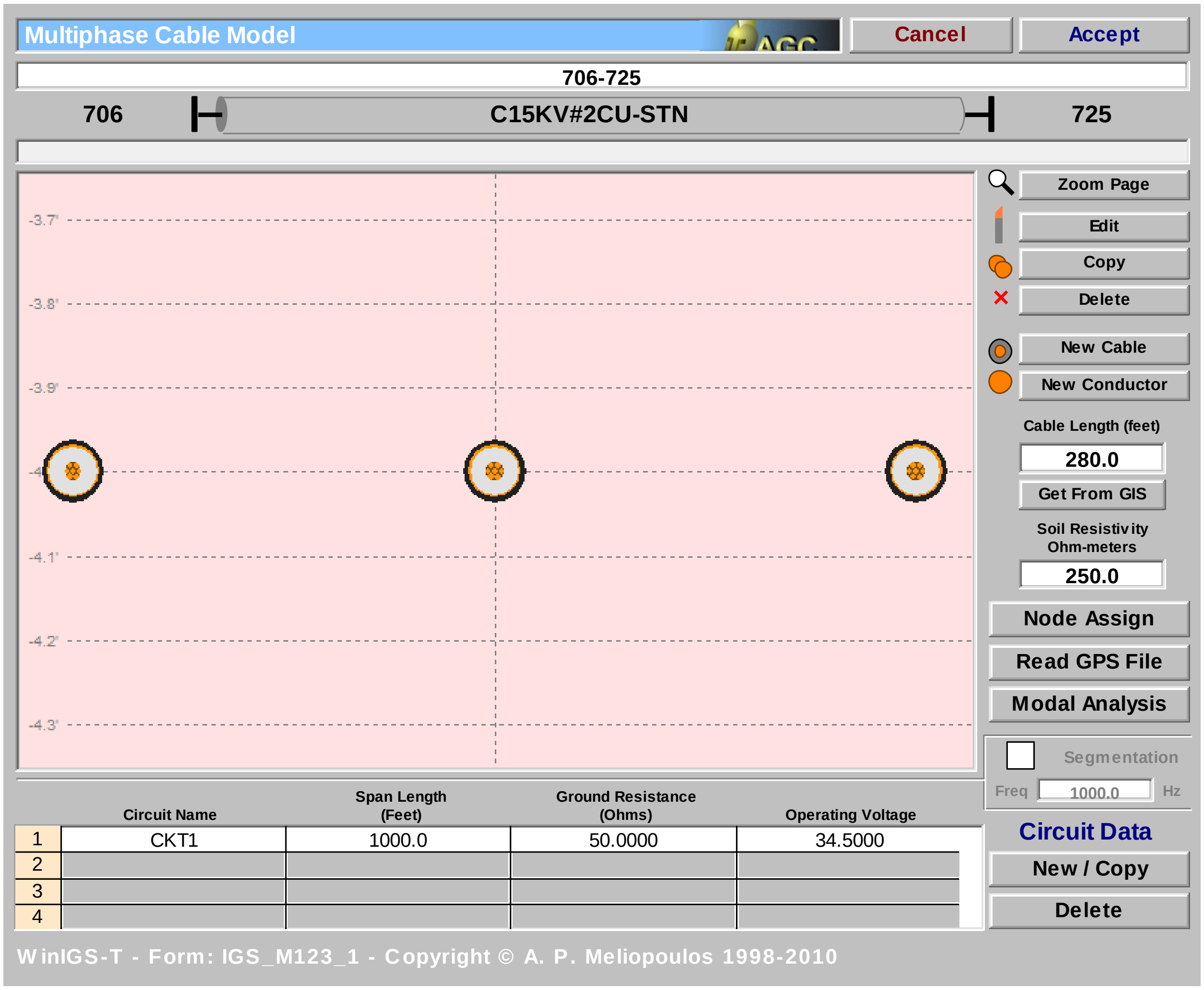


Figure G.15: Configuration 723



	Circuit Name	Span Length (Feet)	Ground Resistance (Ohms)	Operating Voltage
1	CKT1	1000.0	50.0000	34.5000
2				
3				
4				

Figure G.16: Configuration 724

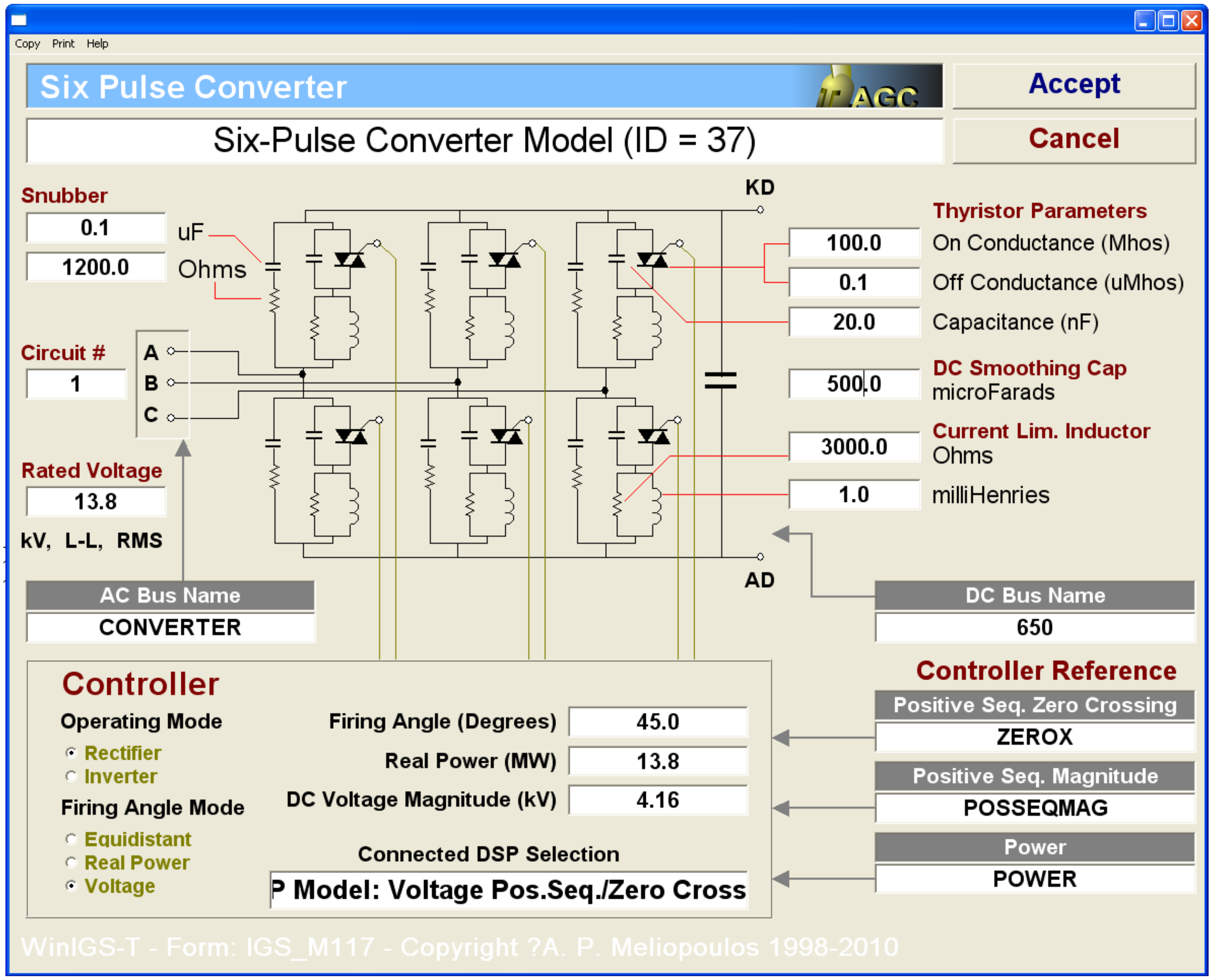


Figure G.17: Six-pulse converter model

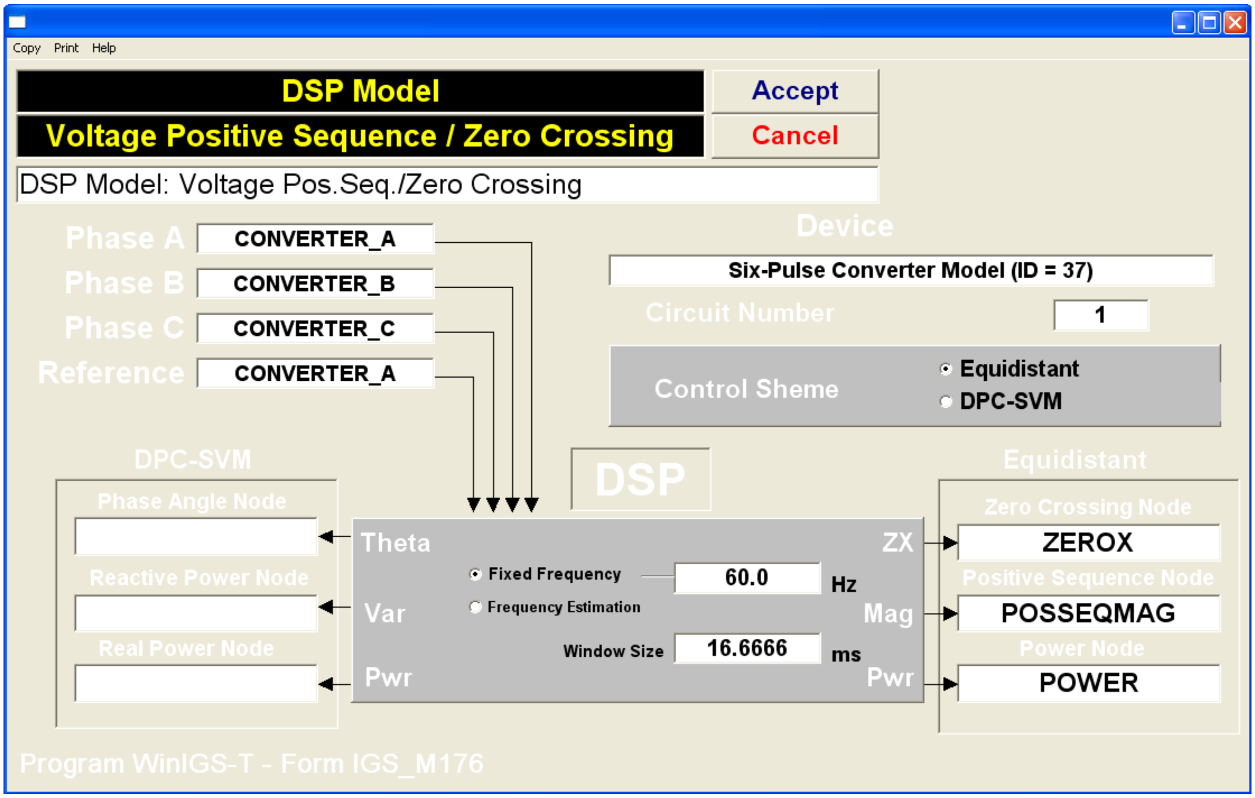


Figure G.18: DSP model for six-pulse converter

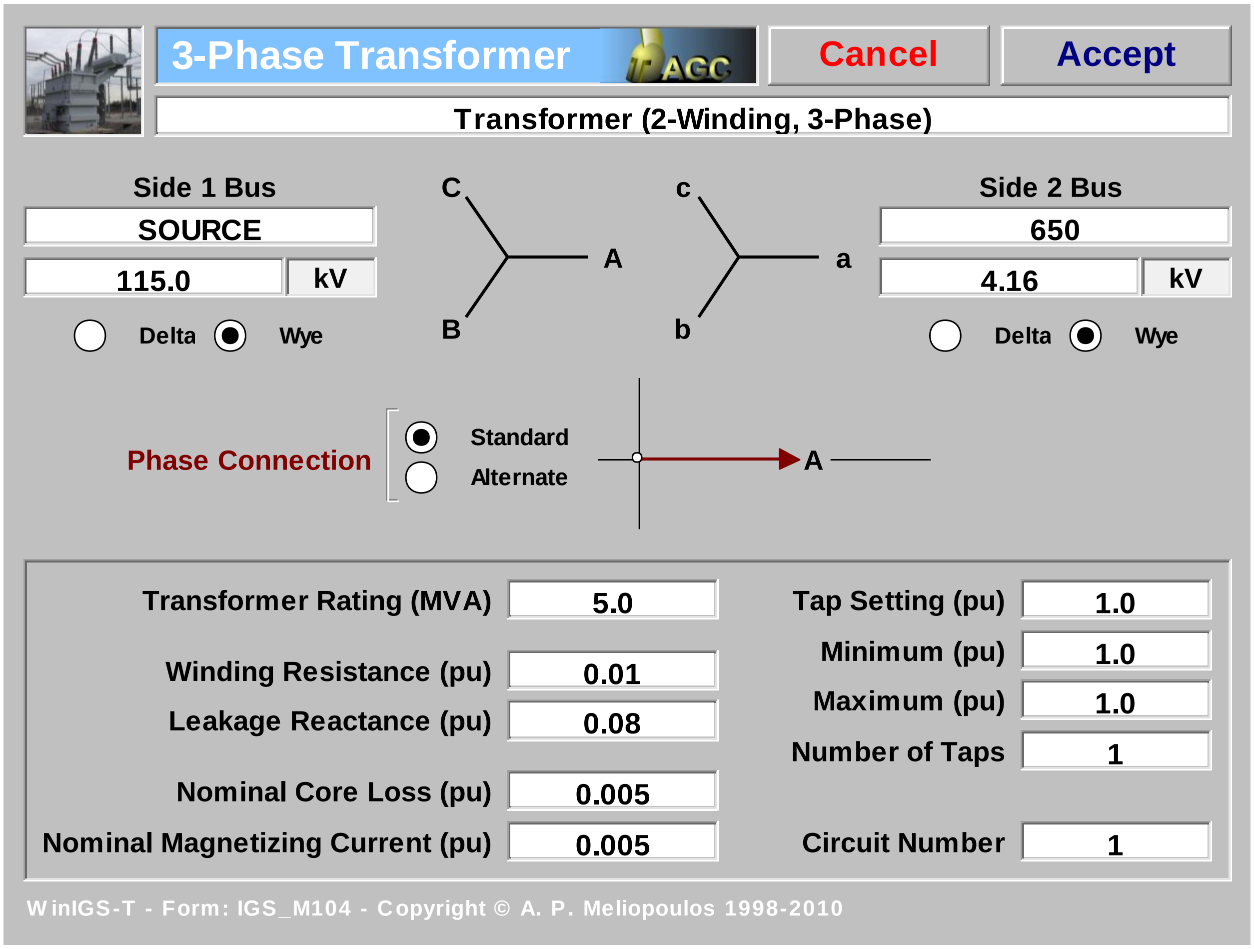


Figure G.19: Source transformer model for first system

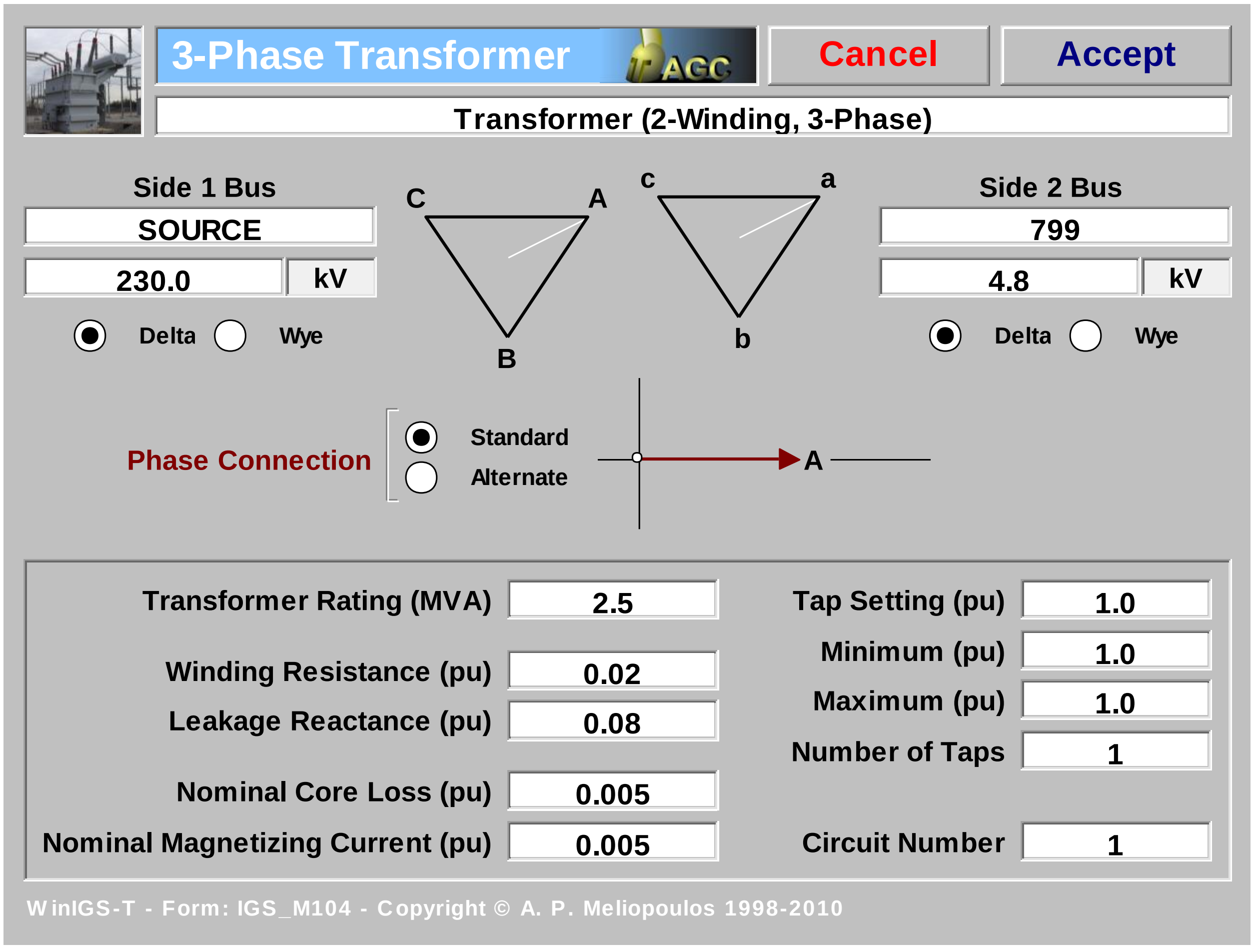


Figure G.20: Source transformer model for second system

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